

## 6.1 Damage Tolerance Analysis Procedure

For intact structure the analysis procedures for Slow Crack Growth and Fail Safe structure are essentially the same. An initial flaw is assumed and its growth is analyzed until failure of the member or load path occurs (or instability and arrest in Fail Safe Crack Arrest structure).

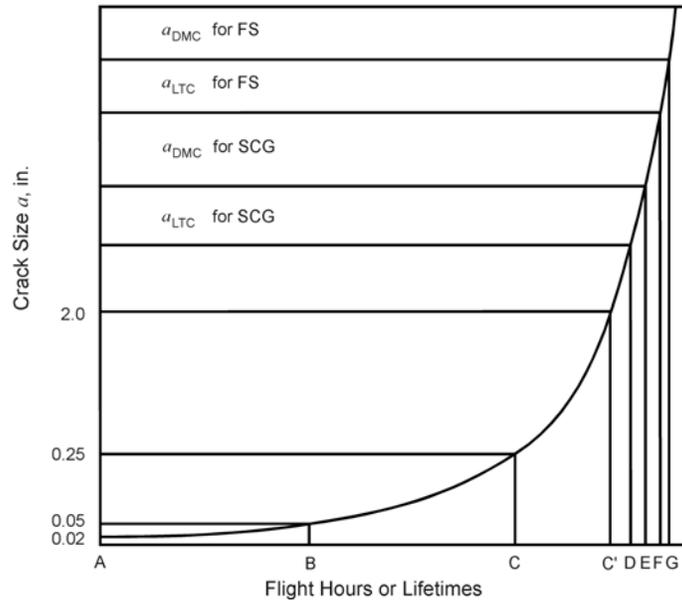
For intact structure, there are two options for the qualification of each type of structure: depot-level inspectable or non-inspectable. The differences are in the assumed initial flaws and the required crack growth life to instability. These requirements are explained in detail in Section 1.3.

After load path failure (or instability and arrest), the damage will be of sufficient size to afford more frequent inspection. As a result, there are more options for qualification of the structure with remaining structure damage depending upon the inspectability of the remaining structure damage. The options are: flight evident, ground evident, walkaround visual, special visual, and depot level. The required crack-growth life with remaining structure damage present depends upon the inspection interval, which increases from one (1) flight to  $\frac{1}{4}$  lifetime. Obviously, these requirements do not apply to slow crack growth structure.

Crack arrest can only occur if there is load transfer from the cracked part to other members (e.g., separate member or reinforcements in the case of Fail Safe structure). However, load transfer does not automatically classify a structure as Fail Safe structure. Only if such load transfer can be shown to give crack arrest, and if the remaining structure requirements can also be met, can the structure be qualified as Fail Safe structure. In all other cases the structure is considered as Slow Crack Growth structure and should be qualified on the basis of Slow Crack Growth requirements.

The crack growth analysis for all types of structures requires the following steps:

- Step 1.** Determine the stress-intensity factor ( $K$ ) as a function of crack size for each member involved. Possible load transfer must be considered, because it may affect  $K$  and this crack growth. (See Section 11).
- Step 2.** Obtain or derive the stress history for the location under consideration. (See Section 5).
- Step 3.** Obtain baseline crack-growth data ( $da/dN$  as a function of  $\Delta K$  and  $R$ ) for all the materials involved, e.g., the skin and the reinforcement members might be fabricated from different materials. (Section 7 summarizes data collection programs).
- Step 4.** Using the results of Steps, 1, 2, and 3, calculate the crack-growth curve for each element, using one of the retardation models described in Section 5. Start with a 0.05 inch flaw. The result will be as shown schematically in [Figure 6.1.1](#).



**Figure 6.1.1.** Diagrammatic Crack Growth Curve (SCG = Slow Crack Growth, FS = Fail Safe)

**Step 5.** By using the results of the residual strength analysis (Section 4), plot the critical (first instability) crack sizes,  $a_{DMC}$  and  $a_{LTC}$ , for depot level inspectability (fail safe load  $P_{DM}$ ) and non-inspectable (fail safe load  $P_{LT}$ ). These are shown in [Figure 6.1.1](#).

NOTE: Since  $P_{DM}$  (and  $P_{LT}$ ) differ for slow crack growth and for fail safe categorized structure, four critical crack sizes may have to be considered.

**Step 6.** For slow crack growth structure, check [Figure 6.1.1](#) to determine:

- I. whether BD is equal to or greater than 2 design lifetimes.
- II. whether CE (or C'E) is equal to or greater than  $\frac{1}{2}$  design lifetime.

If only I is satisfied, the structure is qualified as slow crack growth, non-inspectable. If only II is satisfied, the structure is qualified as slow crack growth, depot level inspectable structure. If both I and II are satisfied, it is optional to qualify the structure as non-inspectable, or inspectable. It should be qualified as non-inspectable to avoid costly inspections. If neither I nor II is satisfied, there are three options:

- redesign or lower stress levels until either I or II is satisfied.
- make the structure dismantable and require a special non-destructive inspection. In that case the post-inspection flaw may be assumed 0.05-inch instead of 0.25-inch. Then BE should be equal to  $\frac{1}{2}$  lifetime for qualification as slow crack growth, depot level inspectable structure.
- demonstrate that cracks smaller than 0.25-inch can normally be detected, and show that crack growth from this size to critical covers  $\frac{1}{2}$  lifetime for qualification as slow crack growth, depot level inspectable structure.

To check for potential qualification as Fail Safe structure continue with the following steps:

**Step 7.** Check ([Figure 6.1.1](#)) to determine:

- I. whether AF is equal to or greater than 1 design lifetime.

II. whether CG (or C'G) is equal to or greater than  $\frac{1}{4}$  design lifetime.

If either or both of the two conditions are satisfied the structure might qualify as fail safe structure with the same possibilities as in Step 6. However, classification still depends upon the following steps. If neither condition is satisfied, either redesign or reduce stress levels. (Note that the structure would certainly not satisfy Slow Crack Growth requirements.)

- Step 8.** Determine the size of the arrested crack from the residual strength analysis (Section 4).
- Step 9.** Determine the remaining structure damage as specified in JSSG-2006, the Airplane Damage Tolerance Requirements. First calculate the stress-intensity factor as a function of crack size. The growth of this damage is calculated in the same way as that of the initial damage following Steps 1 through 4.
- for independent structure, a flaw of 0.005 inch should be assumed in the adjacent (uncracked) member. The remaining structure damage is of the size to which this flaw has grown prior to instability and arrest or member failure.
  - two adjacent members in Fail Safe dependent structure have a common source of cracking, so that both have a 0.02 inch initial flaw. If one member fails, the remaining structure damage in the adjacent member is obviously of the size to which the 0.02-inch initial flaw has grown prior to instability of the crack in the first member.
  - in Fail Safe structure, the crack may arrest in a hole. In that case the remaining structure damage is simply a 0.005 inch flaw at the other side of the hole, plus its growth prior to instability. If the crack does not arrest in a hole, remaining structure damage has to be mutually agreed upon by the USAF and the contractor.
- Step 10.** Determine the total damage size by combining the results of Steps 8 and 9. Determine the stress-intensity factor of this damage as a function of its further growth.
- Step 11.** Calculate the post-arrest crack propagation curve, using the stress-intensity factors determined in Step 10 and follow the same procedure as in Steps 2, 3, and 4.
- Step 12.** By using the results of the residual strength analysis (Section 4) plot the critical crack size for the applicable level of remaining structure inspectability; five levels are available. If the life satisfied the requirement for the selected inspection, the structure qualifies as Fail Safe structure provided that the residual strength of the remaining structure at the moment of arrest is adequate. If neither of these requirements is met, the structure does not qualify. In that case, there are two options:
- redesign (e.g., detail design of adjacent structure) or lower stress level.
  - try to qualify the structure as Slow Crack Growth structure by following Steps 1 through 6 (larger initial flaw sizes and longer crack lives are specified in that case).

The following example illustrates, in a much simplified example, the interaction of these decisions and some of the information which can be obtained from the basic crack growth analysis. This example is illustrative only and many of the simplifying assumptions would not be valid for actual design purposes.

### A Simplified Example

It is not immediately obvious whether it is always advantageous to qualify a structure as non-inspectable. This subsection intends to illustrate in which cases higher design stresses can be allowed if the non-inspectable qualification is selected, and in which cases an inspectable qualification would allow higher design stresses. Subsequently, the other advantages and disadvantages of the two cases will be briefly considered.

For Slow Crack Growth structure the required crack-growth life for the non-inspectable case (2 lives from 0.05 inch to critical) is on the order of four times the required life for depot level inspectability (1/2 lifetime from 0.25 to critical). The same holds for Fail Safe structure (1 lifetime from 0.05-inch to critical, and 1/4 lifetime from 0.25 to critical).

Crack-growth curves usually show a sharp rise towards the end of the life. This raises the question whether the structure would not always qualify as non-inspectable if it qualifies as depot level inspectable. For example, in [Figure 6.1.1](#), if CG covers 1/4 lifetime would not AF be at least 1 life; and similarly if CE covers 1/2 life would not BE at least cover 2 lives? If this were so, a depot-level inspectable structure would always qualify as non-inspectable. (A non-inspectable structure would not always qualify as depot level inspectable, however.) Then the inspectable case would be superfluous, since the non-inspectable qualification would always permit the higher design stress.

If the initial damage of 0.05 inch consists of through cracks in skin panels, it can easily be shown that the crack-growth life from initial flaw size to failure is always more than four times the life from 0.25 inch (through crack) to failure. However, this does not hold for the case of cracks at holes. In the following example, an approximate derivation shows in which cases depot-level inspectable qualification would allow higher stresses than non-inspectable structure, and vice versa. It should be emphasized that this example is only an approximation. The results should not be used as a basis for design; each new structure should be considered as a separate case, and be analyzed as such.

The stress-intensity factor for a cracked hole can be given as:

$$K = \beta\sigma\sqrt{\pi a}$$

For simplicity, a fourth power law for crack growth is assumed:

$$\frac{da}{dN} = \phi C (\Delta K)^4$$

where  $\phi$  is an arbitrary retardation factor, used as an average for the whole spectrum (it would be different for different spectra, but this is irrelevant since  $\phi$  will disappear during the derivation).

The growth rate can be integrated to give the crack-growth life as:

$$N = \int_{a_i}^{a_c} \frac{da}{\phi C (\Delta K)^4} = \frac{1}{\pi^2 \phi C \sigma^4} \int_{a_i}^{a_c} \frac{da}{\beta^4 a^2} \quad (6.1.1)$$

In this equation,  $a_i$  is the initial flaw size,  $a_c$  is the critical crack size, and  $\beta$  is a function of crack length and hole diameter. For the non-hole case where  $\beta$  was independent of crack length (for simplicity assume  $\beta = 1$ ), it would follow that:

$$N = \frac{1}{\pi^2 \phi C \sigma^4} \left( \frac{1}{a_i} - \frac{1}{a_c} \right) \quad (6.1.2)$$

Also:

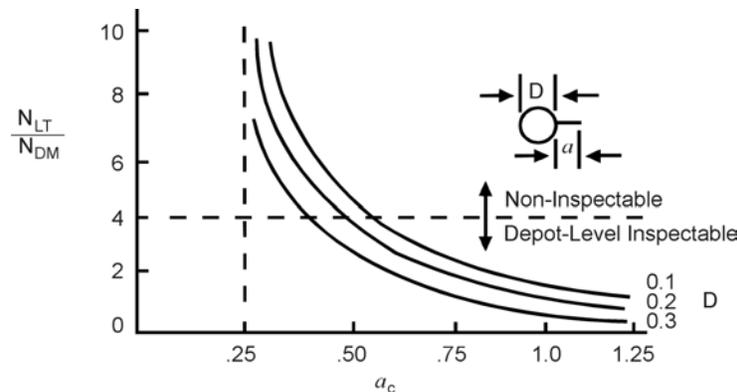
$$\frac{N_{LT}}{N_{DM}} = \frac{\frac{1}{a_{iLT}} - \frac{1}{a_{cLT}}}{\frac{1}{a_{iDM}} - \frac{1}{a_{cDM}}} \quad (6.1.3)$$

where the subscript  $LT$  refers to the non-inspectable case, and  $DM$  refers to the depot-level inspectable case.

Using the proper function for  $\beta$  for a radial crack at a hole, Equation 6.1.1 was evaluated to give the equivalent of Equation 6.1.3. For Slow Crack Growth structures,  $a_{iLT} = 0.05$ -inch and  $a_{iDM} = 0.25$  inch. The critical cracks  $a_{cLT}$  and  $a_{cDM}$  were taken equal, because the last part of the crack-growth curve is very steep, (i.e., the difference in life would only be small if  $a_{cLT} \neq a_{cDM}$ ). For Fail Safe structures,  $a_{iLT} = 0.25$  inch. Also here  $a_{cLT}$  and  $a_{cDM}$  were taken equal.

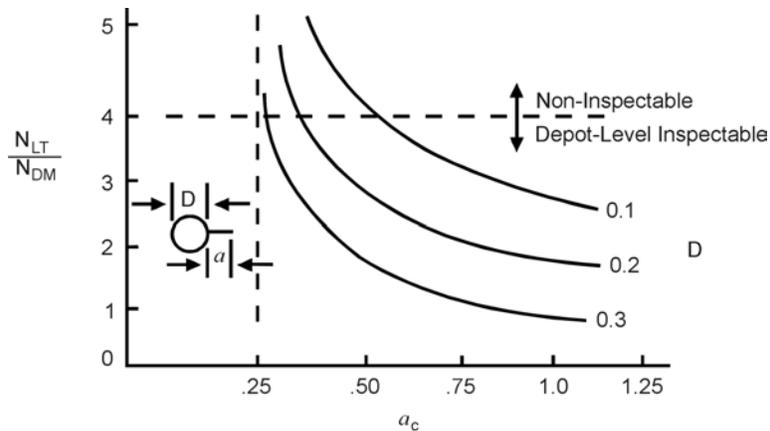
On the basis of these numbers, the equations were numerically evaluated as a function of the critical crack size ( $a_c$ ) for various hole sizes. The results are shown in [Figures 6.1.2](#) for Slow Crack Growth and [6.1.3](#) for Fail Safe. The abscissa gives  $a_c$ ; it could be converted into  $K_{Ic}$  (or  $K_c$ ) since

$$a_c = \frac{K_{Ic}^2}{\pi \beta^2 \sigma_{DM}^2}$$



**Figure 6.1.2.** Design Curve for Slow Crack Growth Structure

For cracks at holes, the ratio  $N_{LT}/N_{DM}$  becomes smaller than 4 above a certain value of  $a_c$  (when the material has a sufficiently high toughness). The larger the hole diameter, the smaller the crack size at which  $N_{LT}/N_{DM} < 4$ . In view of the small initial crack size (more life is spent in crack growth to 0.25 inch) these numbers are somewhat larger for Fail Safe structures ([Figure 6.1.3](#)).



**Figure 6.1.3.** Design Curve for Fail Safe Structure

In the regime  $N_{LT}/N_{DM} > 4$ , it is easier to qualify the structure as non-inspectable. If the total life from  $a_i$  to  $a_c$  just covers two lifetimes (1 life for Fail Safe structure, the life from 0.25 to  $a_c$  will fall short of  $\frac{1}{2}$  life ( $\frac{1}{4}$  life for Fail Safe structure)). The crack-growth life might be so long that it still qualifies as both inspectable and non-inspectable. That means that the structure is oversized.

As an example, consider a Slow Crack Growth structure with  $a_c = 0.35$ -inch and  $D = 0.2$ -inch.

According to [Figure 6.1.2](#) this would have  $N_{LT}/N_{DM} \approx 6$ . For the structure to qualify as depot-level inspectable,  $N_{DM}$  has to be at least  $\frac{1}{2}$  life. Then  $N_{LT}$  would be at least 3 lives ( $N_{LT}/N_{DM} = 6$ ), whereas 2 lives would be adequate to qualify as non-inspectable. If crack-growth is assumed approximately inversely proportional to  $\sigma^4$  (since  $da/dN = CAK^4$ ) the design stress could be increased by a factor of  $(3/2)^{1/4} \approx 1.11$ . The structure would still qualify as Slow Crack Growth, non-inspectable, but not any more as depot-level inspectable ( $N_{DM}$  would only be  $\frac{1}{3}$  life).

On the other hand, if the toughness were high enough to give  $a_c = 0.75$  inch, an inspectable structure could be designed to a higher stress. For  $D = 0.2$  inch, the ratio  $N_{LT}/N_{DM}$  would be on the order of 2.5 ([Figure 6.1.2](#)). If  $N_{LT}$  would still be equal to 2 lives, then  $N_{DM}$  would be  $2/2.5 = 0.8$  life. In order to qualify for depot-level inspectability, the stress could be raised by a factor of  $(0.8/0.5)^{1/4} = 1.12$ . In that case,  $N_{DM}$  would be  $\frac{1}{2}$  life, but  $N_{LT}$  would only be  $2.5 \times 0.5 = 1.25$  lives. Hence, qualification as non-inspectable would require 12 percent lower stress than qualification as depot-level inspectable.

Similar examples can be given for Fail Safe structure. The smaller initial crack sizes work slightly in favor of the non-inspectable qualification. It should be borne in mind, however, that the primary crack-growth requirements here may not be decisive for the design, because the remaining structure damage requirements have to be met also.

As might be expected, longer critical crack sizes favor qualification as depot-level inspectable at higher allowable stresses than qualification as non-inspectable. Longer critical crack sizes are also beneficial for the total crack-growth life. Therefore, qualification as non-inspectable is more easily attainable with high toughness materials.

A depot-level inspectable structure has advantages and disadvantages. Safety is ensured by sufficiently slow growth of cracks of inspectable sizes (large critical crack size) and by periodic inspections. However, the necessity of inspection is a burden to the operator, and it may make

the design less attractive. Besides, safety does depend on the adequacy of inspections. If a crack is not detected in a timely manner, failure will still occur.

Non-inspectable structures will generally be somewhat heavier. Safety is ensured by a sufficiently long crack-growth life. The inadequacies and deficiencies of the damage tolerance analysis (which are the same as for inspectable structure) are not partly compensated by periodic inspections. If the crack growth analysis would be a factor 2 in error, a catastrophic failure might still occur within one lifetime. This could be prevented if the structure were inspectable.

The latter considerations are less applicable to Fail Safe structures. Their safety is ensured by adequate remaining structure damage behavior, and by the fact that the large damage after load path failure (or instability and arrest) is easier to detect. Consequently, pre-instability requirements can be less stringent, and are more of economical significance than in the case of Slow Crack Growth structure.