PROBLEM NO. MERC-1

Title: Crack Growth Prediction of Center Wing Component with Emphasis on β-Factor Determination

Objective:

To illustrate the process of applying finite element and boundary element analyses to the determination of β-factors for crack growth simulations

General Description:

This problem focuses on the determination of β-factors for crack growth analysis of a longeron in the center wing area. Both 2-D and 3-D numerical methods are applied in the analysis. FRANC2D/L, a 2-D finite element (FE) analysis program, is used for the β-factor determination of through cracks. FRANC3D, a 3-D boundary element (BE) program is used to determine β-factors of a corner crack.

Topics Covered: finite element analysis, boundary element analysis, β-factor calculation

Type of Structure: center wing, longeron

Relevant Sections of Handbook: Sections 2, 5, 11

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Critical Area

This problem focuses on a critical area of an angle longeron in a center wing. As shown in the finite element mesh below, the crack starts in, and grows across the horizontal leg of the angle longeron. It begins as a corner crack in a fastener hole where the longeron and upper splice bar are attached.

The dominant loading mode of the longeron is tension during banking and turning maneuvers, but due to the complex geometries and interactions of the components, the details of the stress state are more complicated than simple, uniform tension near the critical fastener. The determination of β-factors through analytical means can, therefore, introduce significant errors in the crack growth analysis. Numerical methods such as finite and boundary element analysis provide a powerful alternative to the analytical solutions.

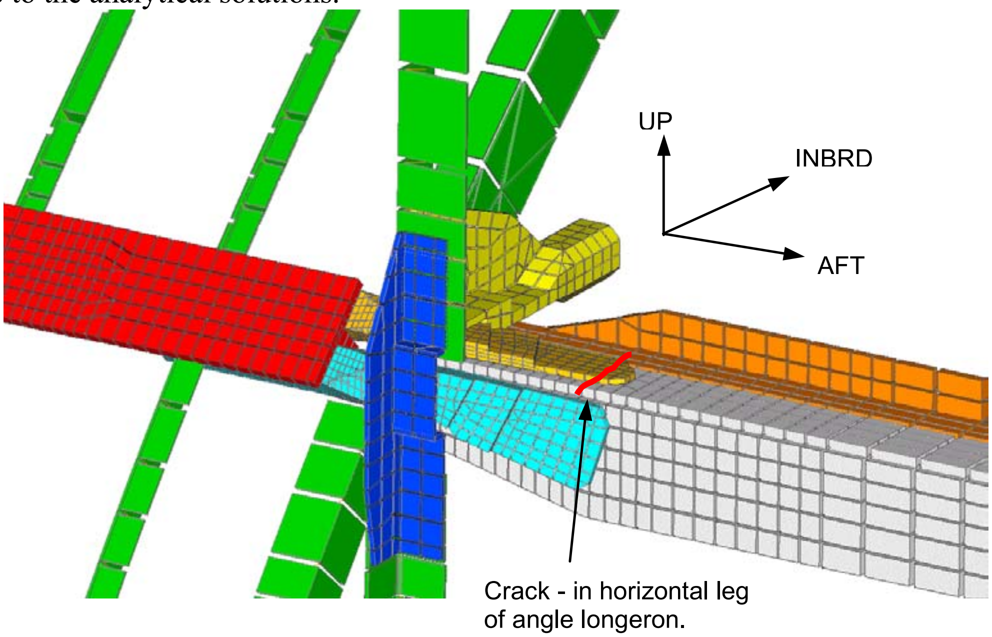


Figure MERC-1.1. Finite element mesh of center wing longeron and neighboring components. The crack location in the horizontal leg of the longeron is indicated.

Crack Growth Phases and Modeling Approach

As shown in Figure MERC-1.2 below, crack growth behavior can be divided into phases, usually alternating between "corner crack growth" and "through crack growth". The odd- numbered phases are corner cracks, and the even-numbered phases are through cracks. Also, it will be assumed here that the phases of crack growth take place sequentially. Corner crack growth starts in Phase 1 and continues until it grows through the part's thickness, at which point, through crack growth begins in Phase 2. Finally, Phase 3 does not begin until Phase 2 growth reaches the free edge of the longeron (Analysis has shown that the crack reaches critical length during Phase 3, therefore analysis of subsequent phases is not necessary.).

The β-factors for each phase of crack growth will be determined somewhat differently, due to the increasing complexity of each phase. Emphasis is placed on the numerical methods used for Phases 2 and 3.

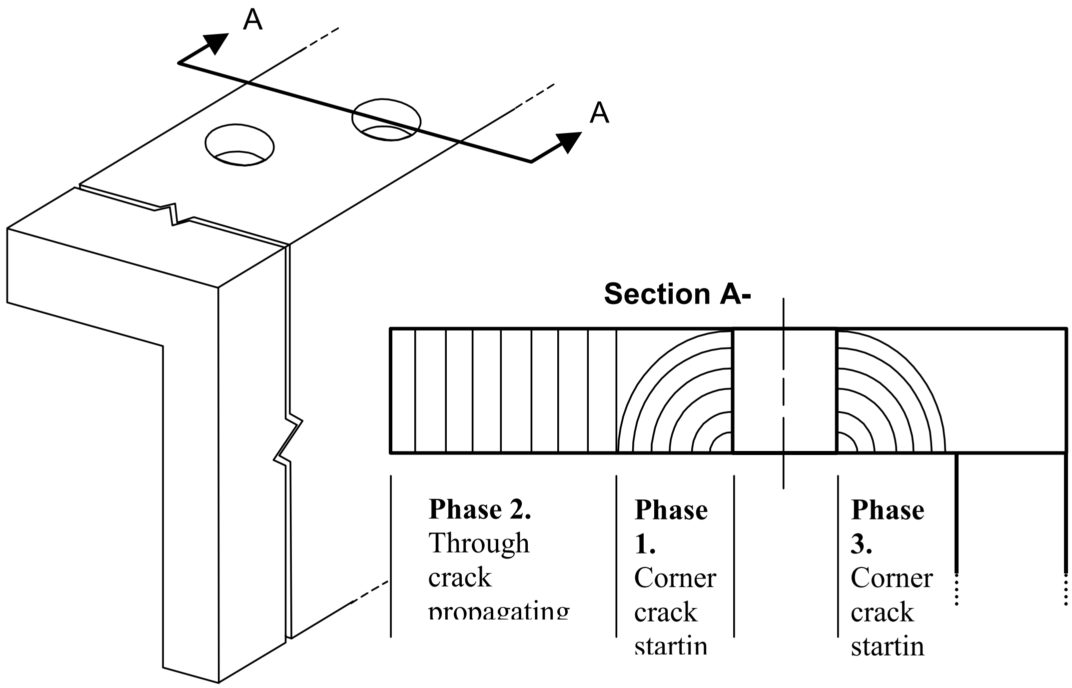


Figure MERC-1.2. Different Phases of Crack Growth in the Longeron are Shown

Phase 1 - Corner Crack at Fastener Hole

This represents a corner crack emanating from a loaded fastener hole that is offset from the center of the longeron leg. AFGROW provides pre-programmed solutions of β-factors for this case. Therefore, relatively little user expertise is required to obtain β-factors here, at least when compared to subsequent phases. Figure MERC-1.3 shows the AFGROW input form for defining part geometry, including the crack, from which AFGROW automatically computes β-factors.

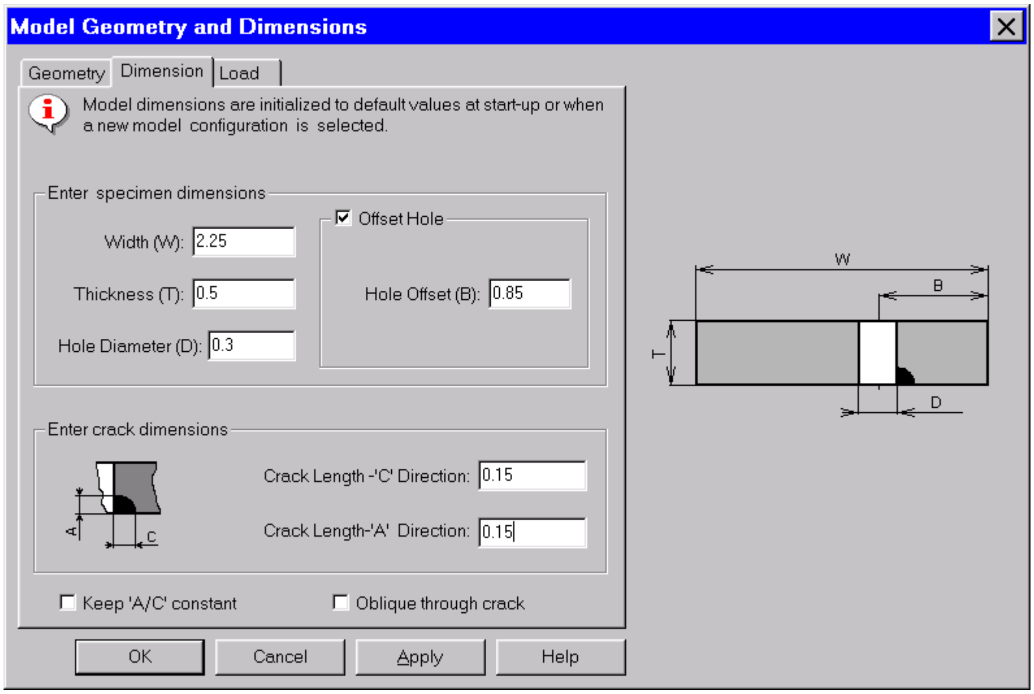
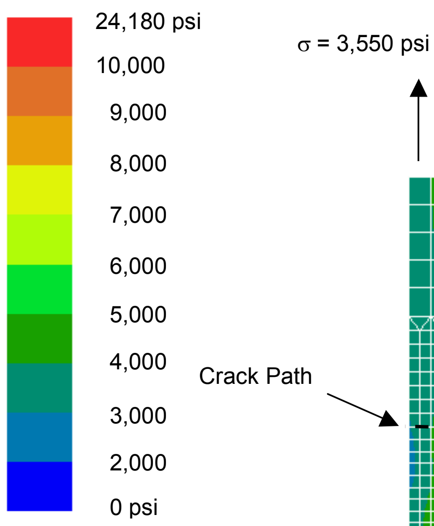
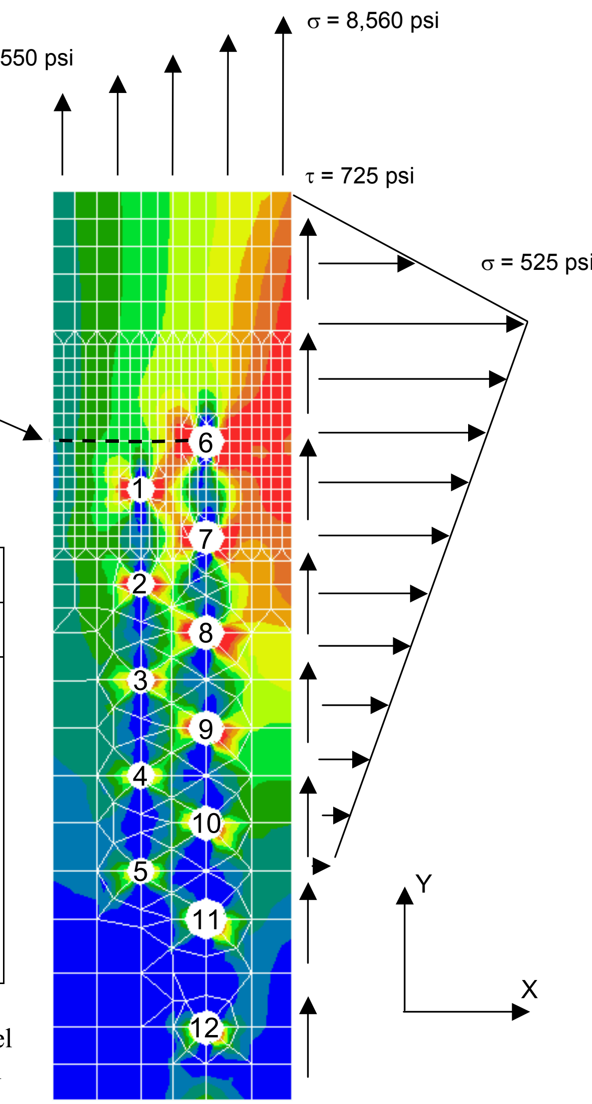


Figure MERC-1.3. AFGROW input form for defining part geometry, including the crack, from which AFGROW automatically computes β-factors.

Phase 2 - Through Crack Growing from Fastener Hole

Part geometry and loading conditions introduce complexities into the second phase of crack growth that are not fully incorporated into existing β-factor solutions. Therefore, numerical methods, i.e., finite elements, are used to estimate the β-factors. Figure MERC-1.4 shows a 2-D FE model of the longeron's horizontal leg developed in FRANC2D/L. FRANC2D/L is chosen because of its ability to automatically remesh while "growing" the crack. The boundary conditions, tractions and fastener forces, are determined from the NASTRAN FE model shown in Figure MERC-1.1. The crack path is also shown in Figure MERC-1.4. Note that it passes nearby a fastener whose presence introduces additional stress concentrations that further complicate the problem.





Fastener Forces (lbs)		
Number	**X-dir**	**Y-dir**
1	-36	-571
2	-59	-541
3	-49	-526
4	-77	-498
5	-123	-873
6	-7	-923
7	-27	-897
8	-24	-893
9	-96	-904
10	-106	-839
11	-184	-987
12	-165	-1200

Figure MERC-1.4. FRANC2D/L model showing principal stresses in horizontal leg of angle longeron

FRANC2D/L computes K values versus crack length as it automatically propagates the crack and remeshes. β-factors are determined by defining a reference stress, which is usually a remote tensile value, and solving for β in Eq. (1).

$$K = \sigma_{ref}\,\beta\sqrt{\pi a} \qquad (1)$$

where K is the stress intensity factor, a is crack length, and σ_{ref} is the reference stress, in this case 6,800 psi. Both K and β values are shown in the graph below.

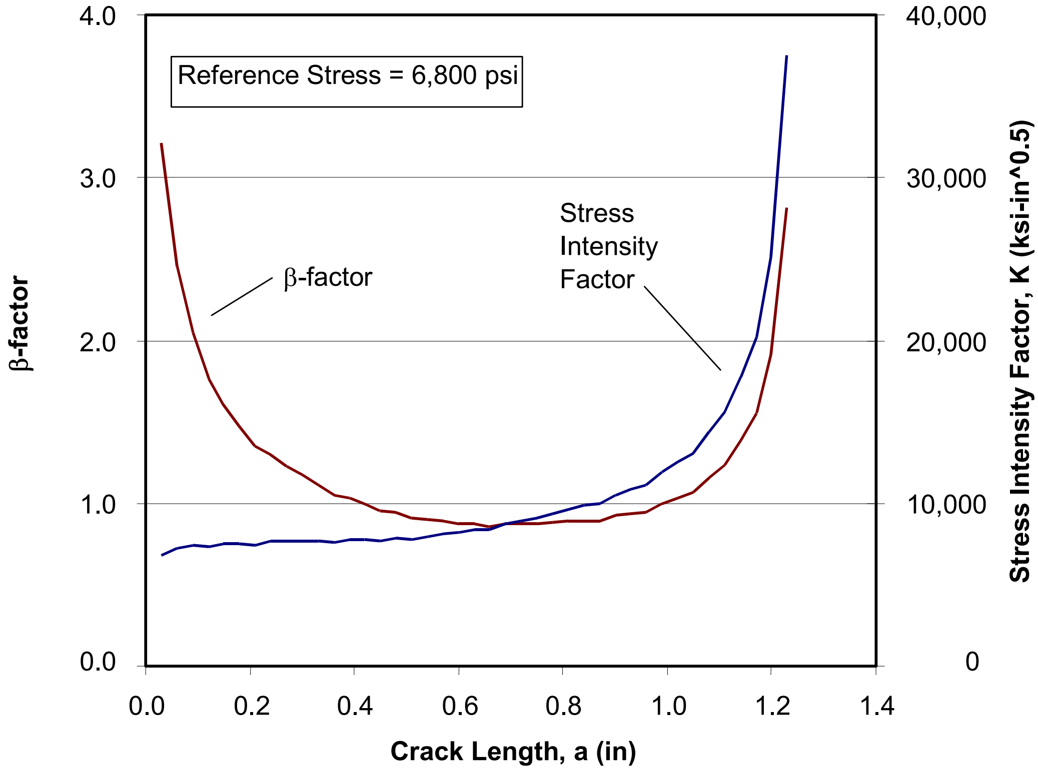
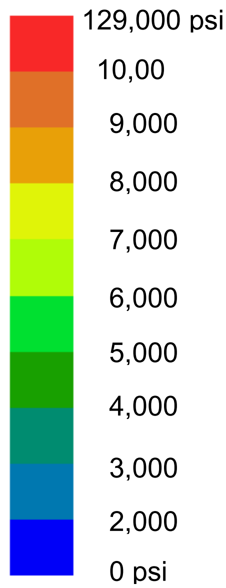
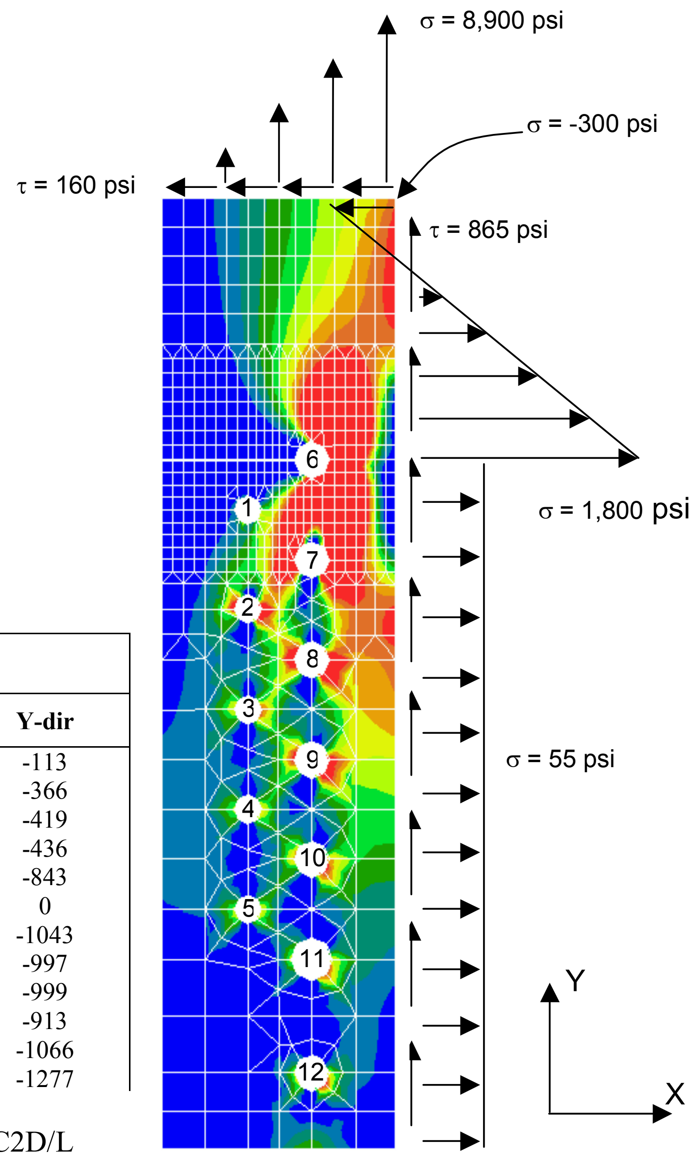


Figure MERC-1.5. β-factors and stress intensity values for Phase 2 of crack growth in the longeron. Values determined by FRANC2D/L

Phase 3 - Corner Crack Growing from Opposite Side of Fastener Hole

In Phase 3, a corner crack is assumed to grow from the opposite side of the fastener hole after the through crack reaches a free edge in Phase 2. But unlike Phase 1, AFGROW does not provide β-factor solutions for this situation. It is necessary to compute them numerically as in Phase 2. The process is substantially more involved because the problem is 3-D, however, it does begin just as the Phase 2 case. The NASTRAN and FRANC2D/L models are developed just as before, but the Phase 2 crack is present. The FRANC2D/L model is shown in Figure MERC-1.6 below.





Fastener Forces (lbs)		
Number	**X-dir**	**Y-dir**
1	309	-113
2	-42	-366
3	-97	-419
4	-122	-436
5	-177	-843
6	0	0
7	121	-1043
8	-47	-997
9	-137	-999
10	-145	-913
11	-238	-1066
12	-289	-1277

Figure MERC-1.6. FRANC2D/L model showing principal stresses in horizontal leg of longeron with crack

The FRANC2D/L model results in Figure MERC-1.6 are used as boundary conditions for another, still more refined, numerical model. It is a 3-D boundary element model, developed in FRANC3D, of a corner crack at the fastener hole. This is shown in Figure MERC-1.7 below. FRANC3D reports *K* values along the corner crack front, and these are used to calculate β-factors using Eq. (1) just as in Phase 2.

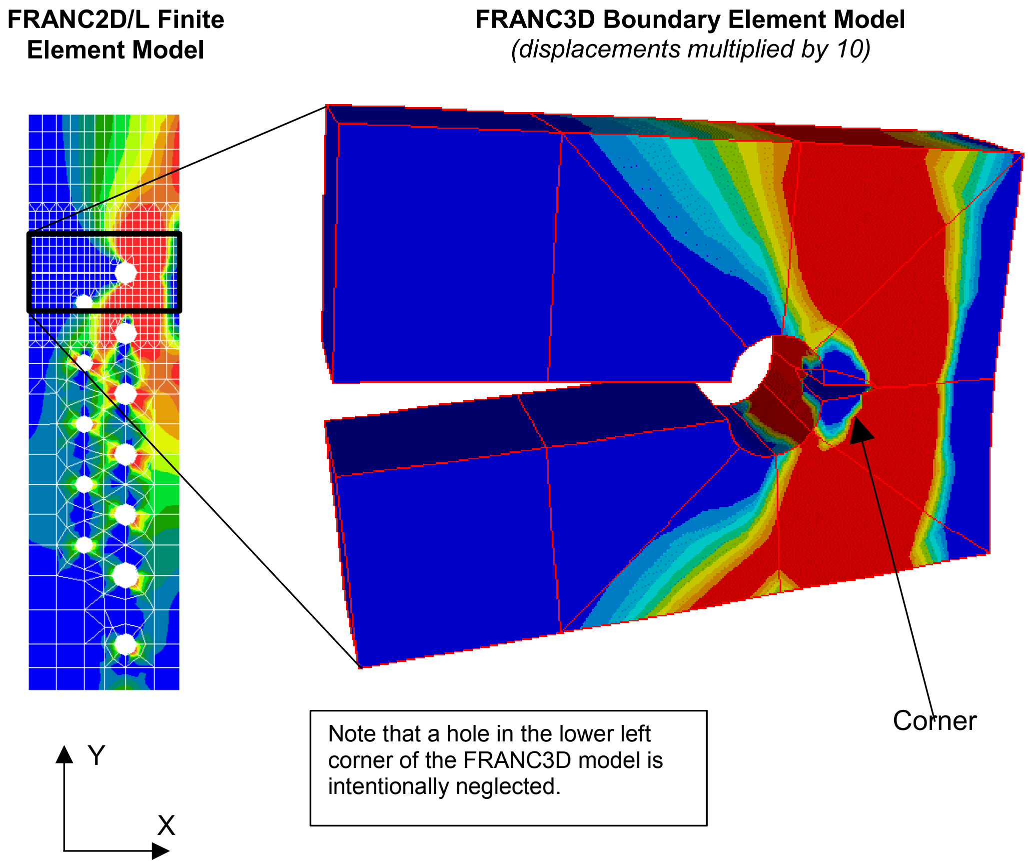


Figure MERC-1.7. FRANC3D model and principal stresses for Phase 3 corner crack at fastener hole. FRANC2D/L stresses serve as boundary conditions for the FRANC3D model

Several FRANC3D analyses are, in fact, necessary for each critical area in order to cover the possible combinations of thickness and surface lengths of the corner crack. As an example, Figure MERC-1.8 illustrates nine (3x3) corner cracks of various lengths that are analyzed in order to provide sufficient β-factor information for corner crack growth studies.

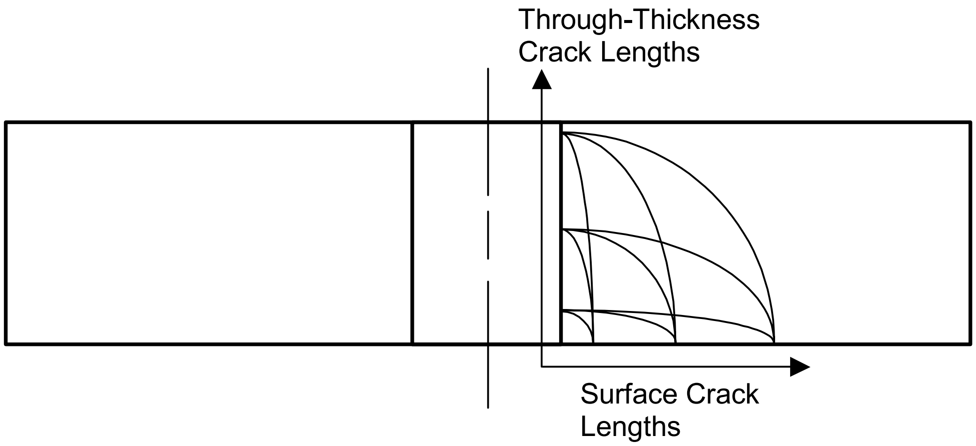


Figure MERC-1.8. Various Corner Crack Geometries that are Analyzed with FRANC3D

Tables MERC-1.1 and MERC-1.2 give β-factors for various corner crack geometries. Two tables are required to determine crack growth through the part thickness and along the part surface. Table MERC-1.1 gives β-factors that apply to crack growth through the part's thickness. Table MERC-1.2 corresponds to crack growth along the part's surface. AFGROW uses this information to independently predict growth rates along the two directions. Though independent, it is generally true that the growth rates produce a corner crack whose thickness length is approximately 50% greater than its surface length.

Table MERC-1.1. Beta Factors – Thickness Direction

		Thickness Crack Length (in)		
		0.05"	**0.264"**	**0.488"**
Surface Crack Lengths (in)	**0.05"**	9.739	4.715	3.219
	0.200"	11.26	8.172	7.940
	0.400"	11.30	11.48	14.62

Table MERC-1.2. Beta Factors – Surface Direction

		Thickness Crack Length (in)		
		0.05"	**0.264"**	**0.488"**
Surface Crack Lengths (in)	**0.05"**	7.590	12.88	14.03
	0.200"	1.381	6.824	11.25
	0.400"	1.211	3.813	10.57

Predicting Crack Growth

AFGROW is used to predict crack growth in the longeron using the β-factors presented here. The crack is assumed to start as a 0.05" radius corner crack at the fastener hole and grow according to the discussion above. Only surface crack length is plotted. Details of the stress spectra and material *da/dN* data are not presented. Note that Willenborg retardation is applied.

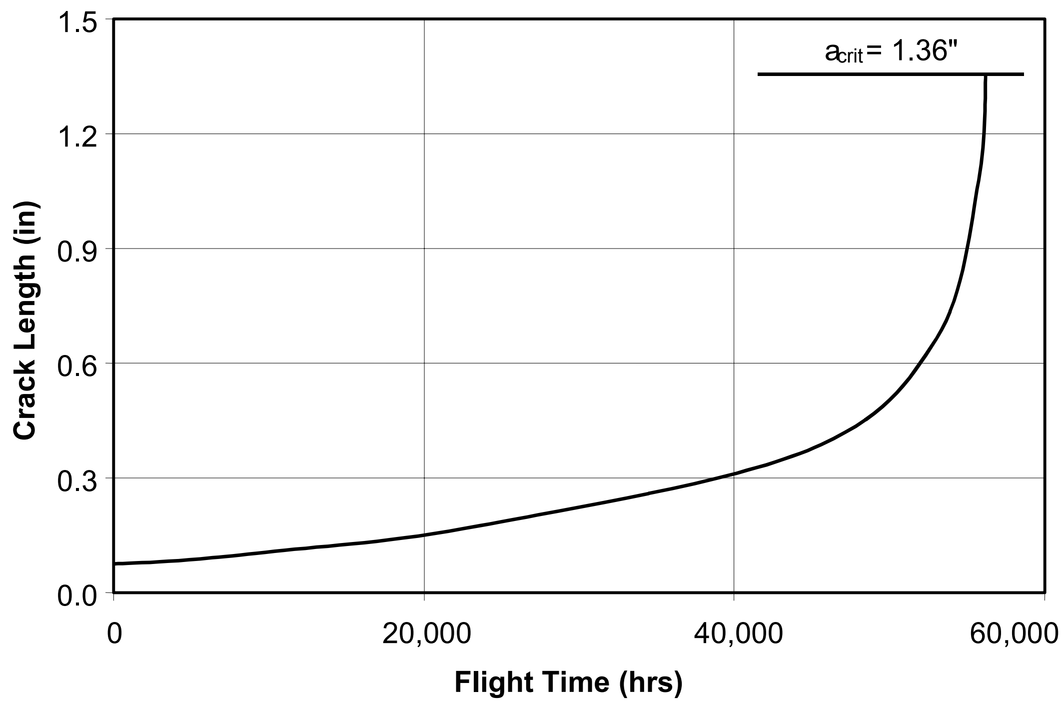


Figure MERC-1.9. Predicted crack growth versus flight hours for a crack growing across the horizontal leg of the longeron. Willenborg retardation is applied to the simulation