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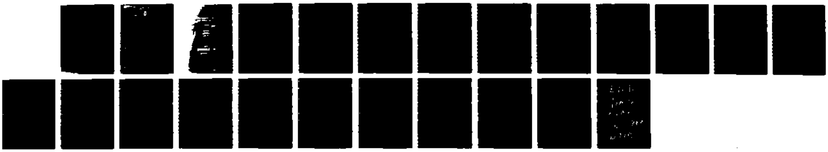

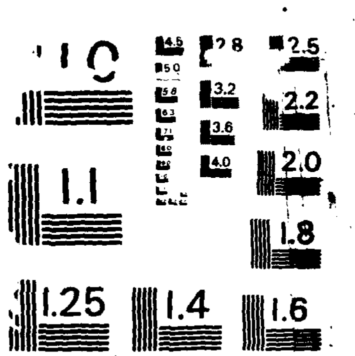

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This study addresses the developement of the Surface-Integral and Finite Element(SAFE) hybrid method for the analysis of short or physically small cracks. In this report, a brief review of representative research papers on fracture mechanics of short cracks is provided. The development of the SAFE hybrid method for materially nonlinear analysis is discussed. Motivation for the use of lumped plasticity models via modelling shear bands at the crack tip is given. Work in progress and future research tasks to be preformed under this contract are outlined. (Keywords)

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SUMMARY

This report pertains to the development of the Surface-Integral and Finite Element (SAFE) hybrid method for the analysis of short or physically small cracks. A brief review of representative research papers on fracture mechanics of short cracks is provided.

The review is focused on the definitions commonly used in distinguishing short cracks from long cracks and the differences that are observed during fatigue crack propagation. The experimental data clearly defines a need to understand the physics of the behavior of long and short cracks. Reasons attributable to these differences are discussed.

The formulation of the SAFE method for fracture mechanics is outlined. Results are provided for long fatigue crack propagation predictions for titanium specimens. The development of the SAFE method for nonhomogeneity and plasticity is presented.

Research plans for modelling plasticity by use of shear bands at the crack tip are also presented.

This annual report covers the period between August 1, 1986 to August 1, 1987. The work reported herein was under sponsorship of the AFOSR under the technical direction of Dr. G. Haritos.

1.0 INTRODUCTION

Structural components are made from materials which have undergone a variety of manufacturing processes. Inherently, the materials contain flaws such as inclusions, voids, porosities, microcracks etc. (refer to Fig. 1, Ref. 1). The presence of a flaw thus has to be accounted for in the design of structural components. These flaws can grow, especially under fatigue loading, and it is important from a damage tolerance point of view to be able to predict the evolution of these flaws.

Fracture mechanics has been developed and applied successfully for the analysis of cracks and associated crack propagation. The Griffith-Irwin linear elastic fracture mechanics (LEFM) theory has been adequate for modelling cracks in structural components where the elastic K fields dominate the solution (Ref. 2). The dominance is usually appropriate when the size of the plastic zone (refer to Fig. 2) is small compared to the length of the crack and other dimensions of the body.

The development of LEFM has been followed by the development of elastic-plastic fracture mechanics (EPFM) with the pioneering work of Hult and McClintock (Ref. 3), Rice (Ref. 4) and Hutchinson (Ref. 5). EPFM is applicable and needed especially for high toughness and low strength materials wherein the elastic K dominance is not satisfied and has to be replaced by J dominance, J being Rice's path independent integral representing the energy release rate. The development of J and associated integrals such as the Wilson-Yu modified J integral (Ref. 6) which account for thermal strains are however based on the deformation theory of plasticity or non-linear elasticity; thus J cannot be applied rigorously after unloading as the crack grows.

The interest in fatigue propagation of short cracks has been motivated by the experimental studies (Ref. 7) which have shown that the growth rate of short fatigue cracks is greater under the same nominal crack driving force than the growth rate for long cracks. It is thus very important to be able to predict growth of these short cracks, as application of long crack fatigue growth analysis will not be applicable and failures may not be predicted.

In this report, a brief description is given for the Surface-Integral and Finite Element (SAFE) hybrid method that has been developed for effective modeling of crack propagation in structural components. Some representative results for long cracks are provided. The development for plasticity along with results is presented.

The motivation for developing lumped plasticity models using shear bands at the crack tip is discussed. The development of the elastic-plastic capability of SAFE is aimed at modelling short (and long) cracks and determining the effect of the plastic zone on crack closure.

2.0 BRIEF REVIEW OF THE LITERATURE

An excellent review of the experimental and analytical work performed on propagation of short fatigue cracks has been provided in the paper by Suresh and Ritchie (Ref. 7). The fatigue process itself is comprised of formation of microcracks due to cyclic damage, coalescence of these microcracks into macrocracks, the subcritical growth of these cracks and subsequent failure of the structural component. The initiation of a crack is a matter of definition as flaws are always present in materials. Initiation in an engineering sense is usually related to the size of the crack which can be readily detected under low magnification. The number of cycles, N_I, to initiation of this crack in an engineering sense has been used to define "life" of a structural component. However, this can be a conservative approach and the "damage tolerance" concept reduces this conservatism by allowing for number of cycles N_P for subcritical crack growth along with appropriate inspection intervals (refer to Fig. 3). The total fatigue life N_T is given by

$$N_T = N_I + N_P \tag{1}$$

N_I is obtained empirically while N_P is obtained either in a test or by analysis. For design purposes, N_P is usually obtained by an analysis which has been well calibrated with actual specimen data. N_P is obtained by using a LEFM approach and the Paris' equation, given below or a suitable variation such as the Forman, Wheeler, Willenborg (Refs. 2, 7) models.

$$\frac{da}{dN} = C(\Delta K)^m \tag{2}$$

where,

- a = crack length
- N = number of cycles
- ΔK = the stress intensity factor range
- C,m = material constants.

2.1 DEFINITIONS OF VARIOUS TYPES OF SHORT CRACKS

Short cracks have been defined in a number of ways. The definitions given below are from reference 7.

(1) Cracks which are of a length comparable to the size of the microstructure, e.g., of the order of the grain size,

(2) Cracks which are of a length comparable to the scale of local plasticity, typically $\leq 10^{-2}$ mm in ultrahigh strength materials and $\leq$ 0.1-1 mm in low strength materials,

(3) Cracks which are physically small $\leq$ 0.5-1 mm.

In this research effort, the second and third definitions will be used for defining short cracks. Also since a two dimensional analysis is being utilized, the crack can be long in the thickness direction. For the first type of crack, anisotropy of the grain will be important; for the ones defined by (2) and (3) EPFM will be necessary for analysis as the elastic K fields may not dominate at the crack tip.

2.2 DIFFERENCES IN OBSERVED RESULTS FOR LONG AND SHORT CRACKS

The experimental work performed by various researchers (Refs. 7-9) has shown that small cracks grow faster than long cracks and application of the Paris equation (2) for the same ΔK gives incorrect results and can lead to overestimates of life (refer to Fig. 4). As can be seen in the figure, the threshold stress intensity factor is different for short cracks than long cracks; also the short crack may arrest or behave as a long crack after it has grown sufficiently.

3.0 SURFACE-INTEGRAL AND FINITE ELEMENT (SAFE) HYBRID METHOD FOR FRACTURE MECHANICS

The Surface-Integral and Finite Element Hybrid method is a very effective method that has been developed for modelling evolution of fractures in finite continua. It combines the best features of the Surface-Integral method which uses dislocations (displacement discontinuities) to model the fracture; and the finite element method for modelling the uncracked body and any inhomogeneity and volume effects. A thesis (Ref. 10) and several papers have been written on this subject (Refs. 11-15).

3.1 FORMULATION OF THE SAFE METHOD FOR LINEAR ANALYSIS

The details of development of the SAFE method are given in references 11-12. The governing equations given below are derived using linear superposition of the Surface-Integral and Finite Element models (Fig. 5) ensuring appropriate traction and displacement matching at the boundaries.

$$\begin{bmatrix} K & G-KL \\ S & C-SL \end{bmatrix} \begin{Bmatrix} U \\ F \end{Bmatrix} = \begin{Bmatrix} R \\ T \end{Bmatrix} \quad (3)$$

where,

K = Stiffness matrix of the plate without the crack
C = Coefficient matrix for the singular integral equation formulation
G = Boundary force correction matrix
S = Stress feedback matrix
L = Displacement matrix for the singular integral equation formulation
U = Total displacement vector at finite element nodes
F = Amplitude of the dislocation density.
R = Applied nodal force vector
T = Applied traction vector along the crack

In Fig. 5, R^c is the boundary force

$$R^c = [G]\{F\} \quad (4)$$

and T^c is the traction along the crack line

$$T^c = [S]\{U^{FE}\} \quad (5)$$

The governing equations for the FE and SI models are:

$$[K]\{U^{FE}\} = R - R^c \tag{6}$$

and

$$[C]\{F\} = T - T^c \tag{7}$$

Also the total displacement field is given by,

$$U = U^{FE} + U^{SI} \tag{8}$$

where,

U^{FE} = Finite element displacements for the plate without the crack

U^{SI} = Surface integral displacements for a crack in an infinite domain

$$U^{SI} = [L]\{F\} \tag{9}$$

using Eqs. (4) through (9) results in the coupled governing Eq. (3) for the SAFE hybrid method.

Results for a wide range of representative problems are given in references 10-15. A typical result for mixed mode fatigue propagation of a long crack in a titanium specimen is given in Fig. 6.

3.2 FORMULATION FOR MATERIALLY NONLINEAR ANALYSIS

The formulation of the SAFE method for material nonhomogeneity is first considered to motivate the development for nonlinear analysis.

3.2.1 Formulation for Nonhomogeneity

In the development of Eq. (3) the material considered was isotropic and homogeneous. Nonhomogeneity in the uncracked body can be easily represented by using appropriate material properties for the finite elements. In the surface-integral model the nonhomogeneity cannot be directly included. However, similar to the boundary force correction vector R^c, a volume correction factor R^{cnh} can be calculated and applied to the finite element mesh. Thus the modified governing equations for nonhomogeneity are given by

$$\begin{bmatrix} K & G-(KL-\overline{K}) \\ S & C-SL \end{bmatrix} \begin{Bmatrix} U \\ F \end{Bmatrix} = \begin{Bmatrix} R \\ T \end{Bmatrix} \tag{10}$$

The additional $\overline{K}$ term appearing in Eq. (10) is obtained from

$$[K]\{U^{FE}\} = R - R^{c} - R^{cnh} \tag{11}$$

where,

R^{cnh} = Additional correction to the load vector due to the presence of nonhomogeneity

$$R^{cnh} = [\overline{K}]\{F\} \tag{12}$$

$$R^{cnh} = \sum_{m} \int_{V^{(m)}} B^{T} \left(I - D_B D_A^{-1}\right) \{\sigma_A^{SI}\} dV^{(m)} \tag{13}$$

$\overline{K}$ = Nonhomogeneity correcton matrix

D_A, D_B = Constitutive matrices, subscript A and B correspond to the material used for the influence function and the nonhomogeneity

σ_A^{SI} = Stresses at the finite element Gauss points due to the surface integral model for homogeneous media.

The summation sign in Eq. (13) extends over all the finite elements. This method has been applied to a problem of a crack in a bi-material plate and good agreement with analytical solutions has been obtained (Refs. 10, 14).

3.2.2 Formulation for Material Nonlinearity

The equations developed for modelling nonhomogeneity are utilized to form the governing equations given below for plasticity via incremental superposition of the surface-integral and finite element models and using equilibrium iteration.

$$\begin{bmatrix} {}^{\circ}K & {}^{\circ}G^{*} \\ {}^{\circ}S & {}^{\circ}C^{*} \end{bmatrix} \begin{Bmatrix} \Delta U \\ \Delta F \end{Bmatrix}^{i} = \begin{Bmatrix} {}^{t+\Delta t}R - {}^{t+\Delta t}\hat{R}^{(i-1)} \\ {}^{t+\Delta t}T - {}^{t+\Delta t}\hat{T}^{(i-1)} \end{Bmatrix} \tag{14}$$

where

$^\circ K$ = Initial stiffness matrix at time t = 0

$^\circ G^*$ = Initial boundary force matrix at time t = 0 ($G^* = {}^\circ G - {}^\circ KL$)

$^\circ S$ = Initial stress feedback matrix at time t = 0.

$^\circ C^*$ = Initial coefficient matrix at time t = 0 ($C^* = {}^\circ C - {}^\circ SL$)

ΔU^i = Incremental total displacement vector at iteration i

ΔF^i = Incremental dislocation density amplitude vector at iteration i

${}^{t+\Delta t}R$ = Applied nodal force vector at time $t+\Delta t$

${}^{t+\Delta t}\hat{R}^{(i-1)}$ = Internal nodal force vector corresponding to the (total) Cauchy stresses at the Gauss points at iteration i-1

${}^{t+\Delta t}T$ = Applied traction vector along the crack at time $t+\Delta t$

${}^{t+\Delta t}\hat{T}^{(i-1)}$ = Internal traction vector corresponding to the (total) Cauchy stresses at the Gauss points at iteration i-1.

The internal nodal force vector and traction vector are calculated as follows (for both elasticity and plasticity):

$$ {}^{t+\Delta t}\hat{R}^{(i-1)} = \int_V B^T \, {}^{t+\Delta t}\tau_{FE}^{(i-1)} dV + \left({}^\circ G + {}^{t+\Delta t}\bar{K}^{i-1}\right) {}^{t+\Delta t}F^{(i-1)} \quad (16) $$

and,

${}^{t+\Delta t}\bar{K}^{i-1}$ = Nonhomogeneity correction matrix (for plasticity) at time $t+\Delta t$ for iteration (i-1).

$$ {}^{t+\Delta t}\hat{T}^{(i-1)} = {}^{t+\Delta t}\tilde{T}_{FE}^{(i-1)} + {}^\circ C \, {}^{t+\Delta t}F^{(i-1)} \quad (17) $$

where,

${}^{t+\Delta t}\tau_{FE}^{(i-1)}$ = Cauchy stresses (due to only the finite element continuous stress field) at time $t+\Delta t$ for iteration (i-1).

${}^{t+\Delta t}\tilde{T}_{FE}^{(i-1)}$ = Smoothed tractions (only continuous stress field) at the collocation points (obtained from Gauss point stresses) at time $t+\Delta t$ for iteration (i-1).

Analysis of a center cracked panel (Fig. 7) for a bi-linear elastic plastic material model has been performed. Results obtained for long cracks by the SAFE method are compared with Hutchinson's (Ref. 5) asymptotic results and reasonable agreement has been obtained (Table 1). The formulation given by Eq. (14) is being further enhanced and convergence issues are being worked out.

At present the model as shown in Fig. 7 still needs use of a large number of finite elements for modelling plasticity. To retain all the best features of the SAFE method it is desirable to capture the plasticity at the crack tip by special schemes. One way of modelling plasticity at the crack tip is by means of shear bands at the crack tips. This is discussed in the following section.

3.3 MODELLING PLASTICITY AT THE CRACK TIP BY USE OF SHEAR BANDS

There are various models such as the Dugdale model (for mode I) and the Bilby-Cottrell-Swinden model (for modes II and III) which have been used to model plastic yielding at the crack tip (Ref. 2). The Dugdale model uses an additional crack length with a yield stress σ_y acting on it to represent the deviation from the elastic singular behavior. Similarly the Bilby-Cottrell-Swinden model uses a distribution of dislocations to model the slip in the additional crack length, for modes II and II. For a crack loaded in uniform tension, for example, it has been reported by Vitek (Ref. 16) and other researchers (Refs. 17-19) that the yielding can be modelled by inclined slip planes at the crack tip. This is like a 'lumped' plasticity model that uses dislocation theory and is suitable for the SAFE method. These models are being studied and current research is aimed at incorporating these in the SAFE code. Particularly for short cracks it is felt that these 'lumped' models will be advantageous.

3.4 FUTURE RESEARCH OBJECTIVES

The current objective is to develop the inclined slip-plane model for plasticity, proceed with modelling cracks emanating from a notch and then develop and implement algorithms for elastic-plastic crack propagation.

Table 1. Elastic and Plastic Stress Intensity Factors

E (psi)	E_T (psi)	Yield (psi)	$\frac{K_I^{el*}}{\sigma\sqrt{\Pi a}}$	$\frac{K_I^{pl*}}{\sigma\sqrt{\pi a}}$	$\frac{K_I^{H**}}{\sigma\sqrt{\pi a}}$	$\frac{K_I^{pl}}{K_I^{H}}$
0.3×10^8	0.15×10^8	3500	1.206	0.85	0.884	0.96
0.3×10^8	0.1×10^8	3500	1.206	0.652	0.735	0.89
0.3×10^8	0.3×10^7	3500	1.215	0.387	0.416	0.93
0.3×10^8	0.1×10^7	3500	1.198	0.208	0.238	0.87

* SAFE analysis
** Based on Hutchinson's bi-linear results.

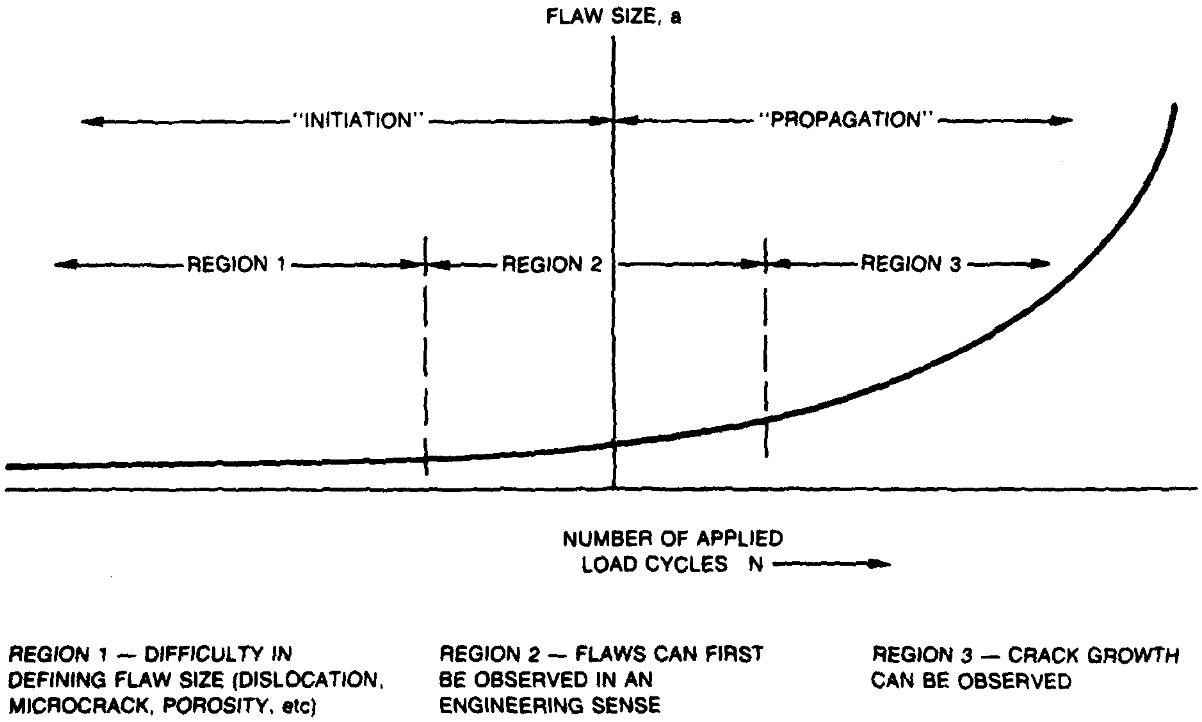

Figure 1. Schematic showing relation between "initiation" life and "propagation" life [1].

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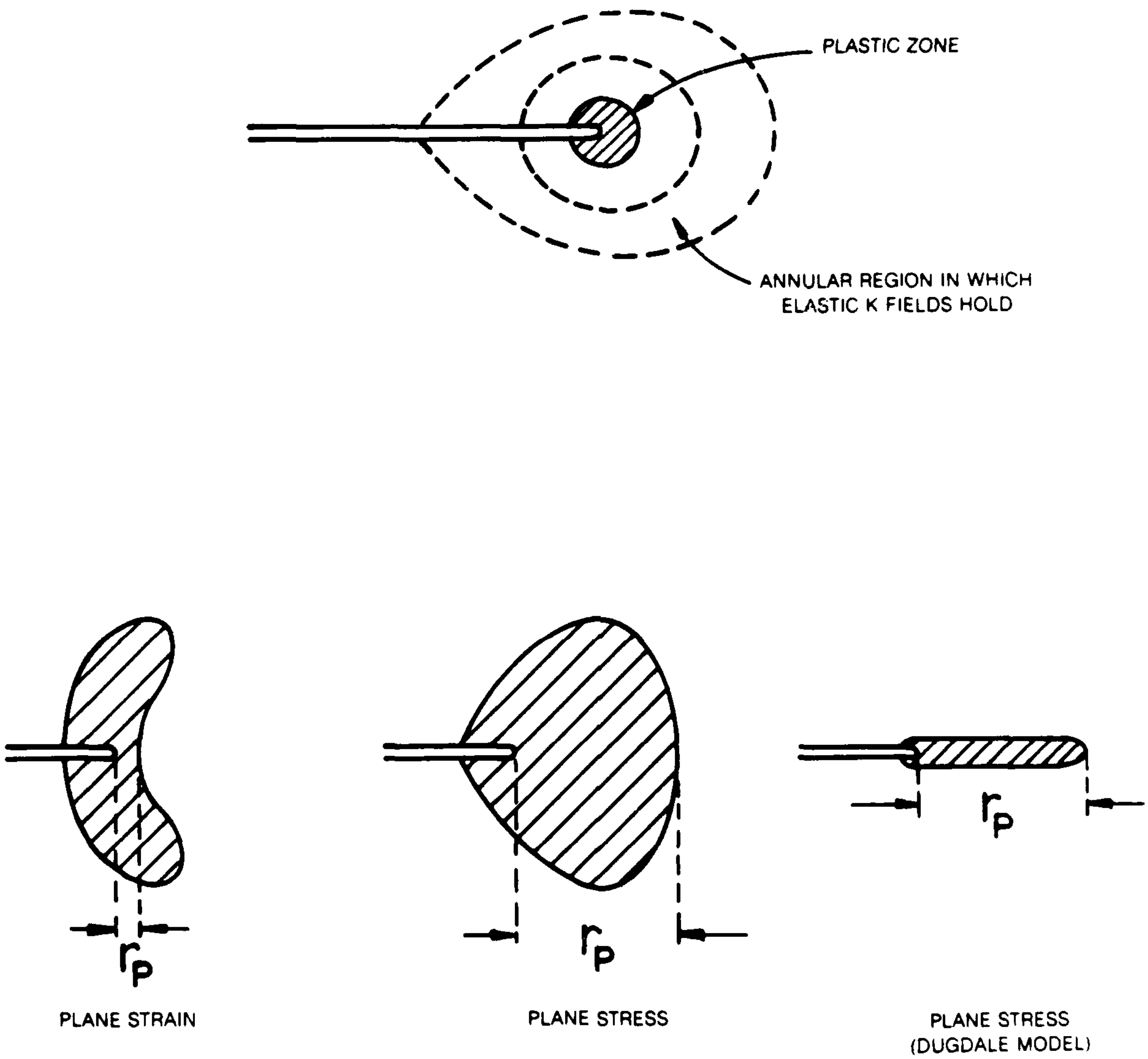

Figure 2. Crack tip plastic zones for various conditions.

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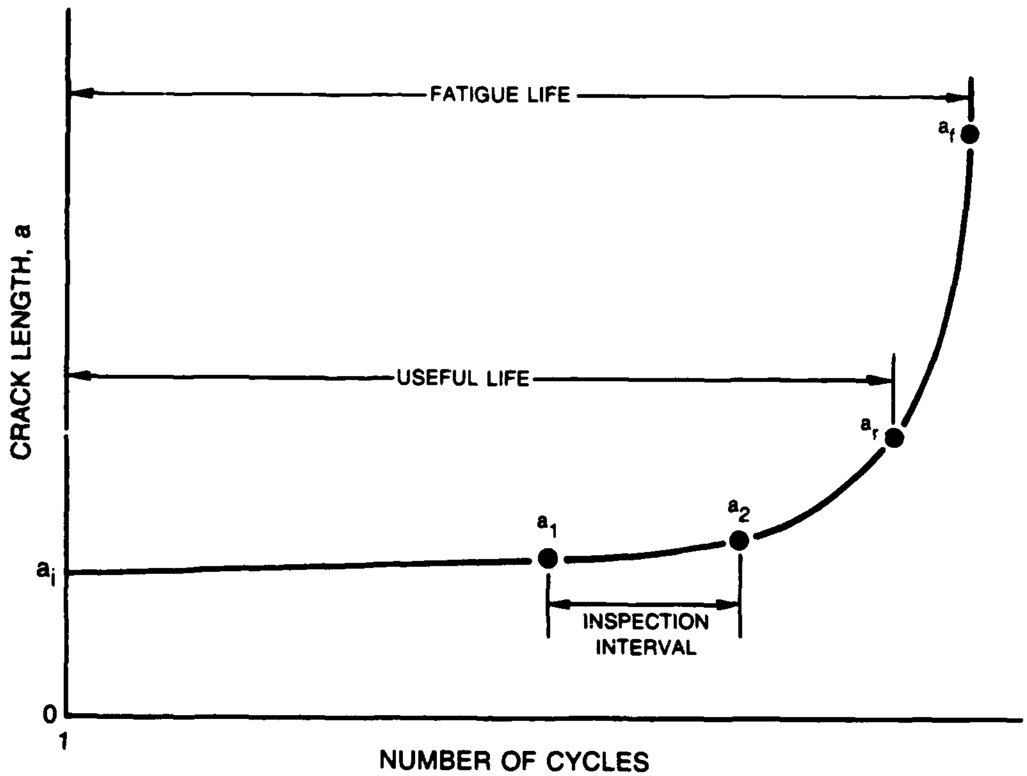

Figure 3. Schematic representation of fatigue crack growth curve under constant amplitude loading [1].

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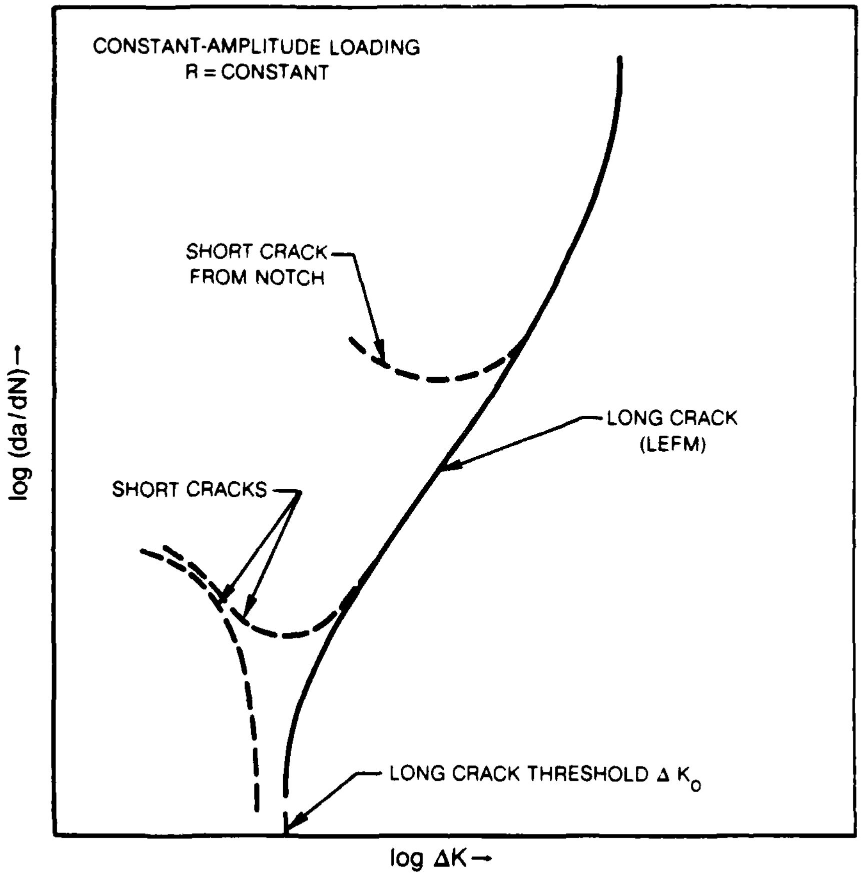

Figure 4. Typical fatigue crack propagation rates (da/dN) for long and short cracks as function of stress intensity factor range ΔK [Ref. 7].

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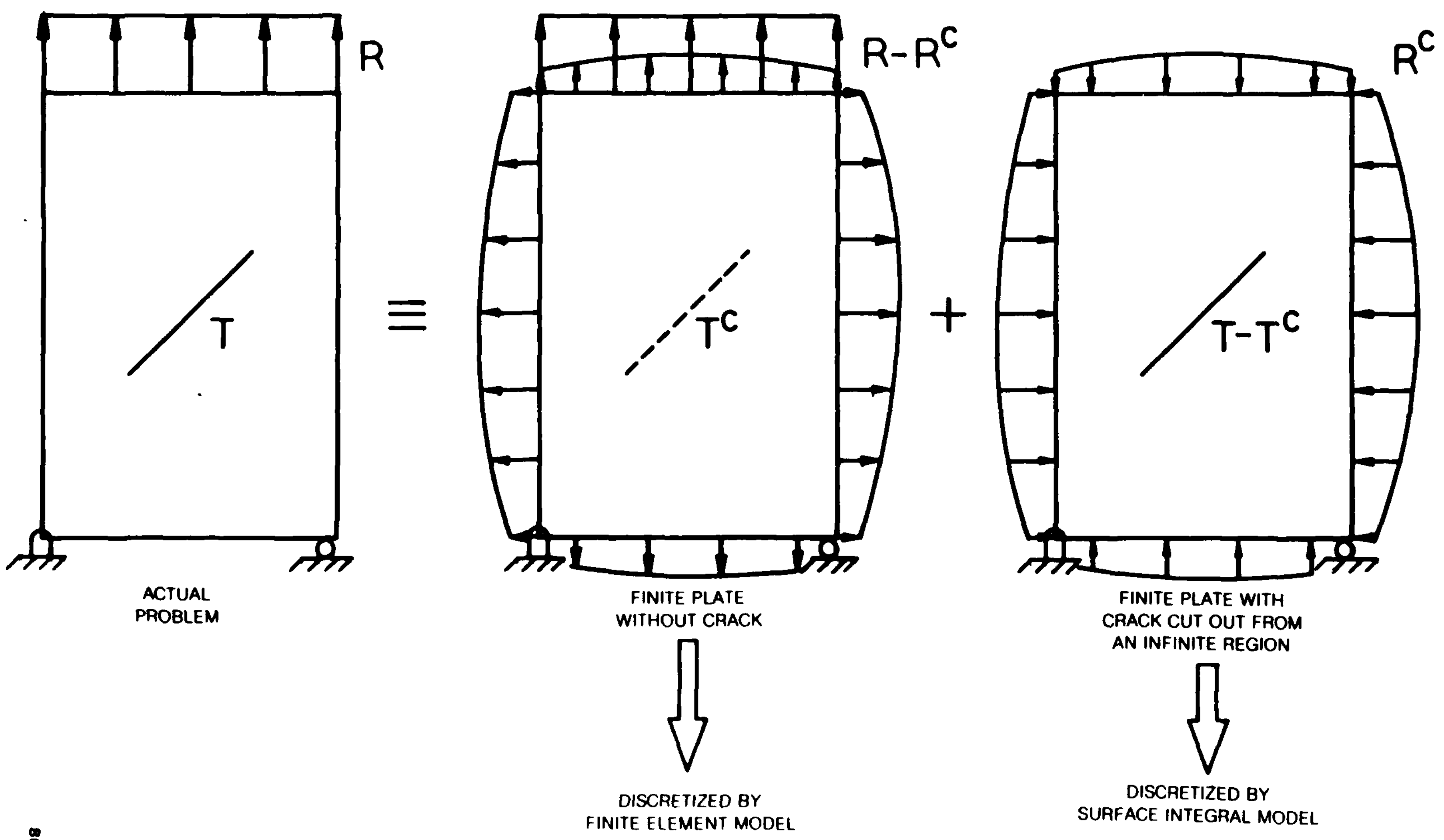

Figure 5. Linear superposition of the finite element and surface integral models.

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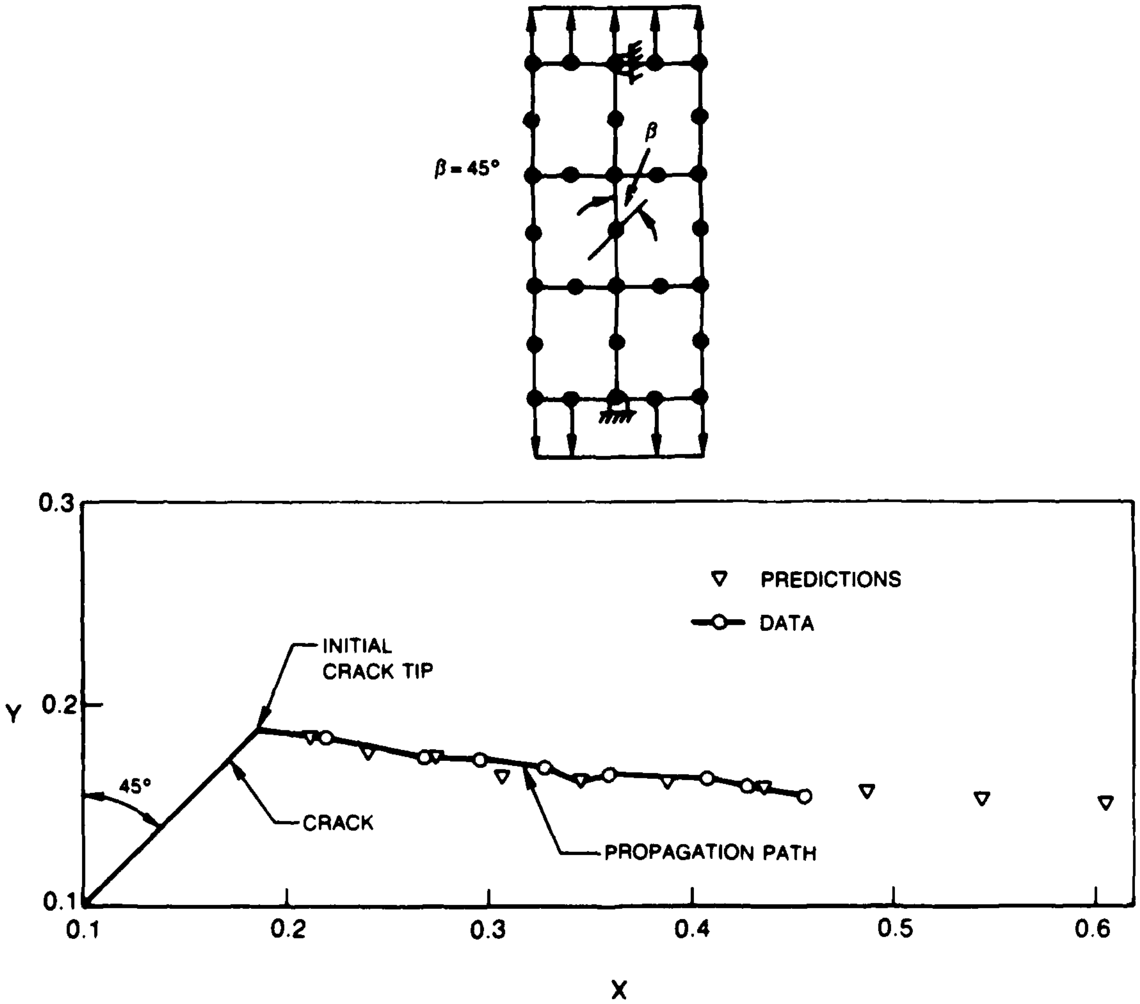

Figure 6. Fatigue propagation of a long crack in titanium.

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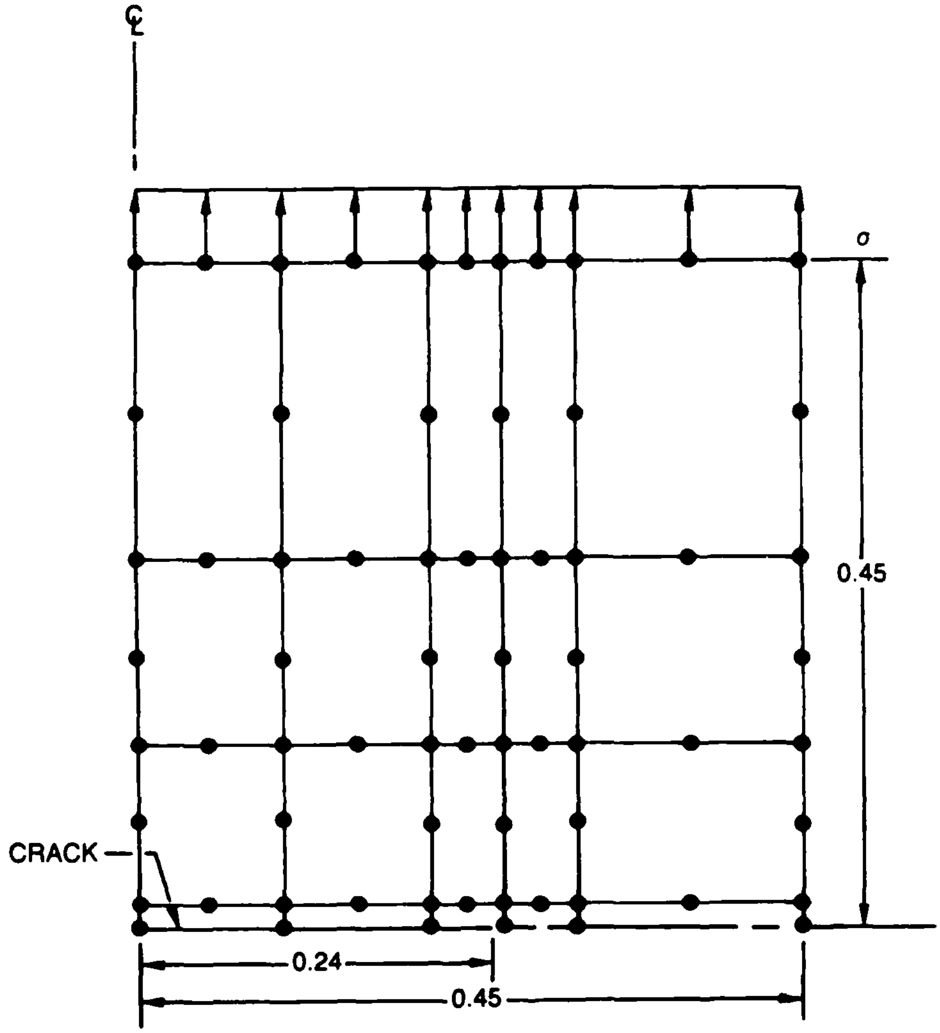

Figure 7. Center cracked test specimen (quarter geometry shown).

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