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DATABASE FOR NON-DESTRUCTIVE FRACTURE FAILURE EVALUATION

by

Kung-Yan Lee

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in
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1986

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December 27, 1985

(date)

Professor in Charge

F. Erdogan

Chairman of Department

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ABSTRACT

A material database has been established for the evaluation of critical flaw size in structural components subjected to fatigue loads. Specimen/size, load amplitude and mean stress and material type can be varied such that their combined effects can be accounted for in determining the condition of global instability. This corresponds to the onset of rapid crack propagation. The computer database permits quick access to material selection and geometry alteration in design.

The concept of non-destructive evaluation (NDE) is also discussed in connection with linear elastic fracture mechanics. A procedure for establishing the particular NDE method is proposed and can be modified for materials that behave nonlinearly. Future development in this area is imminent as quick access to structural integrity evaluation becomes more in demand by the industry.

I. INTRODUCTION

With the advent of modern technology, more sophisticated methodology is needed not only in design but also in evaluating the structural integrity components during service. Unexpected failure can lead to costly repair and delay of production. One of the prerequisites for assessing structural component behavior is a knowledge of the mechanical and fracture properties of materials such that they can be used to forecast the useful life and to develop inspection and/or procedures. Conventional design criteria such as maximum stress, maximum strains, etc. do not yield sufficient information for non-destructive evaluation as they make no reference to the physical dimensions and locations of damage in the material. No reference can thus be established for estimating the remaining life of components under service conditions.

Fracture mechanics became a recognized discipline after World War II because of the inability of continuum mechanics to evaluate failure by fracture. The alarming number of ship structure failures were indicative of the lack of understanding in design against brittle fracture. The fracture toughness and transition temperature quantities [1] were thus introduced to characterize material failure behavior in addition to the conventional mechanical properties such as yield strength, ultimate strength, etc. Most important of all, the interaction of defect or crack size with material comes into play. Allowable load and net section size are thus determined from a knowledge of both uniaxial and fracture toughness data. The standard K_{1c} test as endorsed by the American Society of Testing Material [2] has received worldwide acceptance and been adopted for industrial application. This methodology referred to as Linear Elastic Fracture Mechanics [3], however, could not yield accurate predictions when fracture is preceded by plastic deformation of yielding of the material. The strain energy density criterion [4-7] will thus be adopted for determining the critical condition of fracture. In particular, crack growth resistance curves involving the rate change of strain energy density factor with crack length denoted by dS/da can be developed to reflect the combined effect of loading rate, specimen geometry and size, and material type.

The characterization of the material damage process involving nonlinear behavior is complex and cumbersome as it can involve an overwhelmingly vast amount of numerical data. In addition to having a sound theory, an easily assessable and usable database can provide the practicing engineer with a powerful tool in design. Alternative consideration in material loading can be made. The change in the mode of failure can then be weighed in relation to cost effectiveness. By specifying the nature of loading, material type and specimen geometry and size, the critical crack length at which rapid fracture occurs can be automatically determined from the database in the computer. This includes the time history of crack growth such that non-destructive inspection procedure can be established accordingly.

Developed in this thesis is a database that has the capability of assessing the critical crack size for cracked panels and cylindrical bars by making use of the basic material properties. The corresponding fracture data are computed automatically and used in the failure analysis. A non-destructive evaluation procedure is developed together with sample calculations so that it can be easily used by the ordinary engineer. The main contribution of this work may not lie in the completeness of the database but in developing a quantitative formalism based upon which the database may be broader to cover a wider range of application.

II. STRAIN ENERGY DENSITY CRITERION

Prior to the development of a material database, it is essential to have a valid failure criterion that can realistically characterize the behavior of material for the entire load-time history. This includes the stage of nonlinear stress and strain behavior up to terminal failure. The parameter selected should be sufficiently general such that its fundamental character would be retained as loading material type and specimen geometry are damaged. Up to now, only the strain energy density function dW/dV can satisfy these requirements. In particular, the 1/r behavior of dW/dV with r being the distance measured from the crack front is the same for all material and crack geometry discontinuities. This will not hold for the stress intensity factor approach used in LEFM because the order of the crack front stress singularity changes with the constitutive relation and crack geometry.*

2.1 Mechanical and Fracture Properties

The uniaxial tensile test is most commony practiced in gathering data on material behavior. Depending on the specimen size and loading rate, different response can be obtained in a plot of true stress σ versus true strain ε as shown in Figure 1. As the load is

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*For example, the stress singularity at the point where the crack border intersects with the free surface is different from that in the interior of the solid.

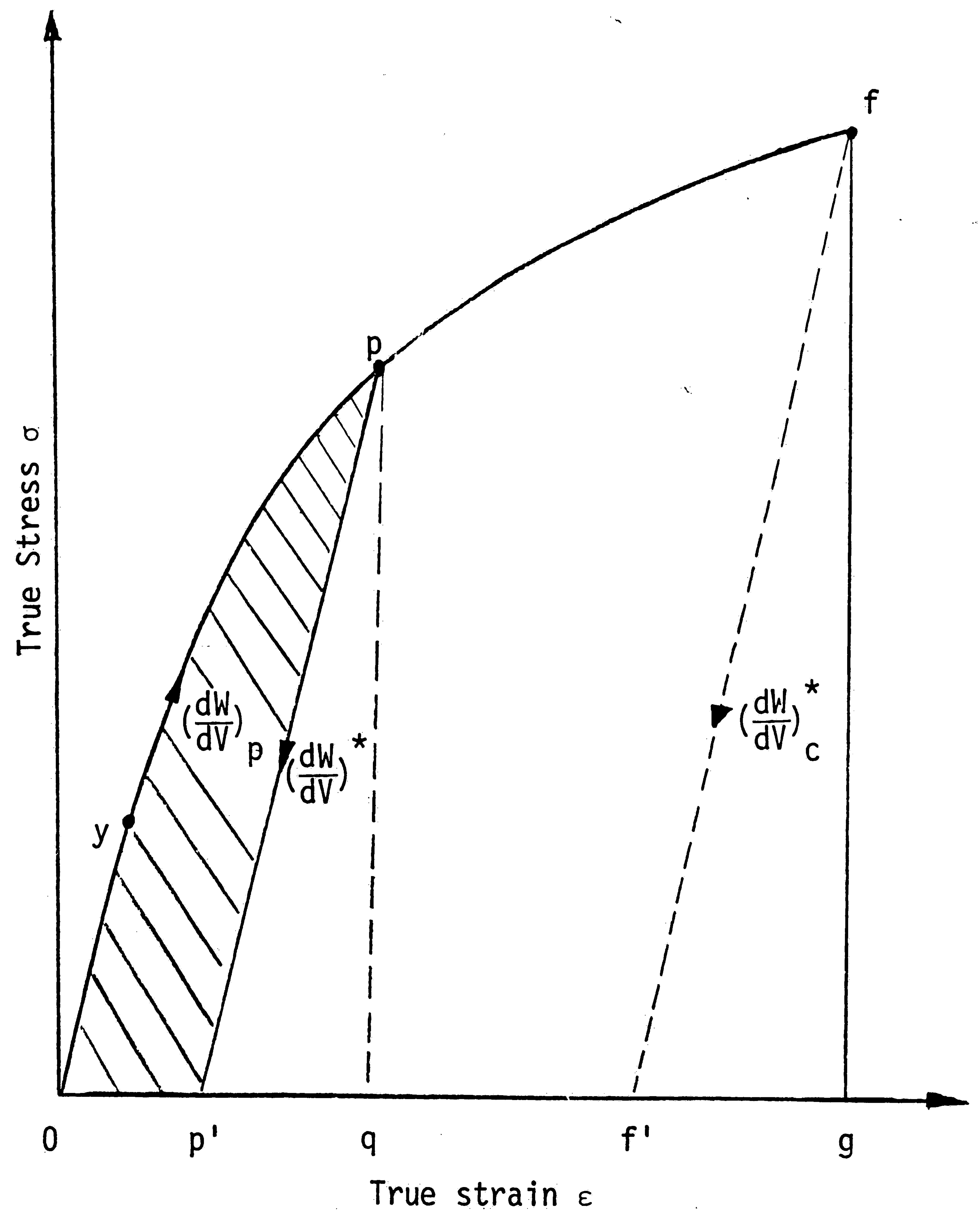

Figure 1. Schematic Of Stress And Strain Curve

increased to the yield point y, a stress level σ_{ys} will be reached beyond which the material will experience permanent deformation. That is, the material will unload along the path pp'. A permanent strain ε_p from o to p will thus be registered. The distance between p' and q is the recoverable strain such that the total strain can be written as

$$\varepsilon = \varepsilon_p + \varepsilon^* \tag{1}$$

Subsequent loading will follow the line p'p rather than oyp. Hence, the area opp' may be regarded as the energy density dissipated during deformation while the area enclosed by p'pq represents the available energy density. They will be denoted, respectively, as $(dW/dV)_p$ and $(dW/dV)^*$ so that the total strain energy density function dW/dV becomes

$$\frac{dW}{dV} = \left(\frac{dW}{dV}\right)_p + \left(\frac{dW}{dV}\right)^* \tag{2}$$

The stress corresponding to the point f at which failure occurs is known as the ultimate stress σ_{ue}. At incipient failure, $(dW/dV)^*$ becomes critical and the amount of energy per unit volume that is available for release is equal to $(dW/dV)_c^*$ or the area f'fg.

In general, dW/dV can be defined in terms of a factor S in the form (Figure 2)

$$\frac{dW}{dV} = \frac{S}{r} \tag{3}$$

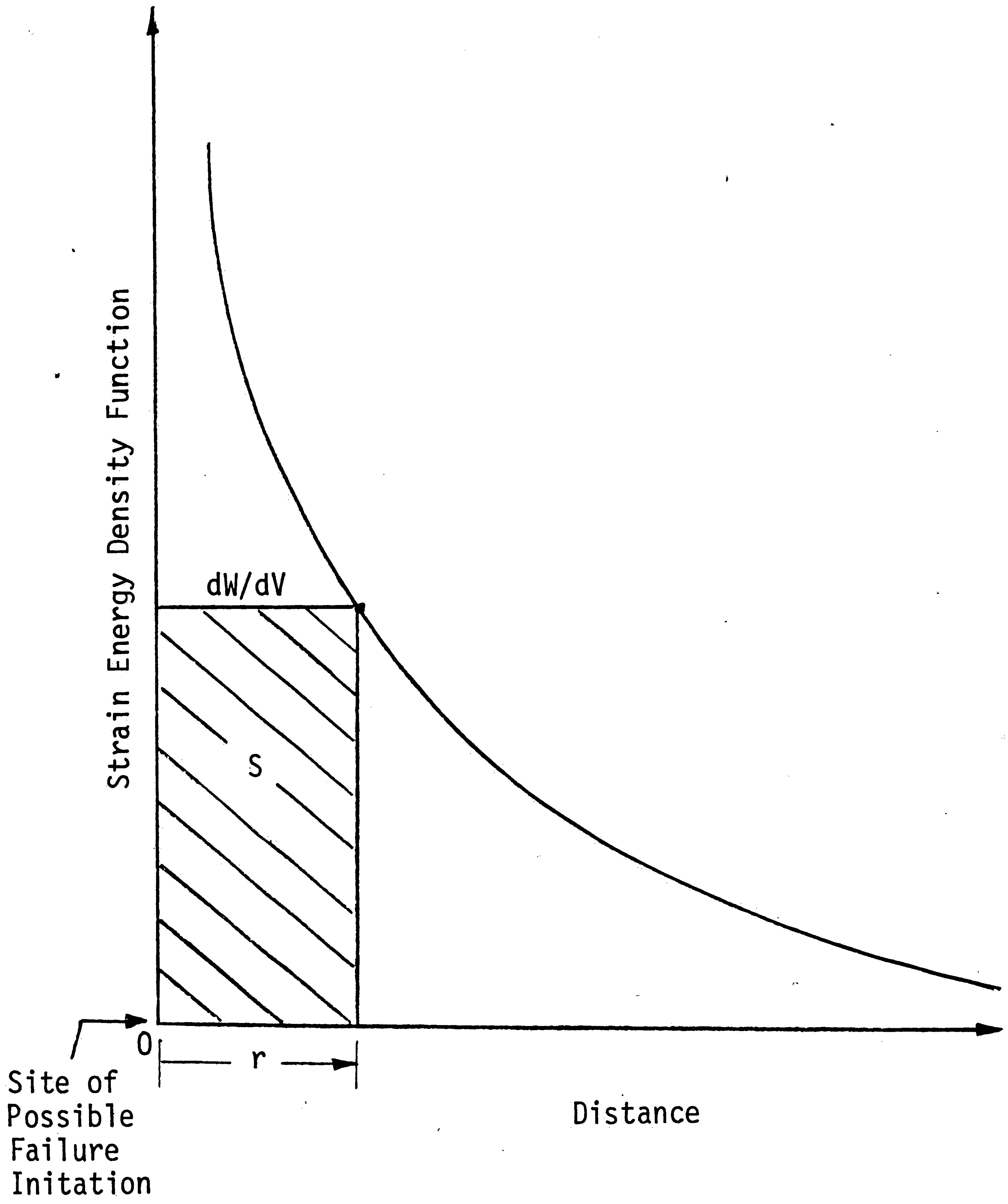

Figure 2. Variations Of dW/dV With Distance Near Site Of Possible Failure.

where r is measured from the site of possible failure such as the crack tip. The function dW/dV generally decreases very rapidly with the distance r. Should the point of investigation o coincide with the crack tip, then the critical value of S or S_c can be interpreted as the fracture toughness of the material i.e., the amount of energy required to extend a unit area of crack surface at incipient fracture. The relation

$$S_c = \frac{(1+\nu)(1-2\nu)K_{1c}^2}{2\pi E} \tag{4}$$

can be used provided that the ASTM plane strain condition

$$\delta \geq 2.5 \left(\frac{K_{1c}}{\sigma_{ys}}\right) \tag{5}$$

is satisfied with δ being the smallest dimension of the specimen such as the plate thickness. In equation (4), ν is the Poisson's ratio and E the Young's modulus.

A typical feature of metal behavior is exhibited by the trade-off relation between yield strength σ_{ys} and fracture toughness S_c as illustrated in Figure 3. The fracture toughness of higher strength metal is usually low. Such a material is proned to brittle fracture. Increase in fracture toughness can only be done at the expense of lowering the strength. For metals with σ_{ys} in the range of 40 to 5,000 MPa and S_c in the range of 900 to 4,000 N/mc, failure will most likely occur in a ductile manner under normal constraint conditions. For very low strength

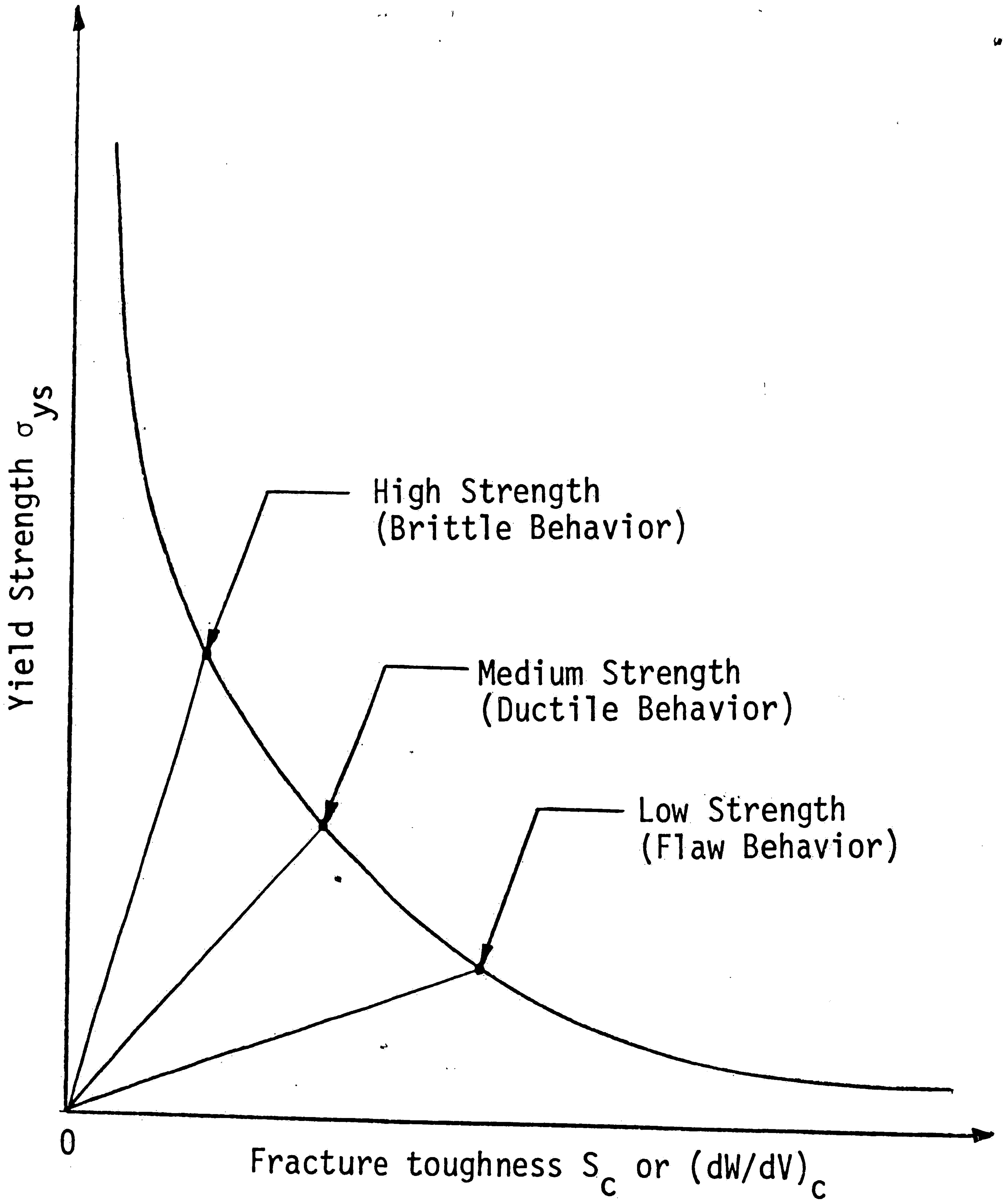

Figure 3. Variations Of Yield Strength With Fracture Toughness For Metals.

materials, metal tends to flow and frequently may not satisfy the stiffness requirement in design. What has been described, of course, applies only to the behavior of materials under uniaxial and normal loading conditions.

In a structural component, the local elements are subjected to triaxial stress states. The local strain rates may be many times higher than those averaged on a global basis. This is mainly because the local mechanical constraints are not uniaxial in character. Care must be exercised in translating uniaxial data to stress states that are multi-axial in character.

2.2 Critical Strain Energy Density

Once the yield point $(\sigma_{ys},\varepsilon_{ys})$ and failure point $(\sigma_{ue},\varepsilon_{ue})$ are known, a stress and strain curve may be generated to obtain the strain energy density function dW/dV which is the area under the curve. To this end, use will be made of the Ramberg-Osgood relation

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E} & , \quad \sigma \leq \sigma_{ys} \\ \dfrac{1}{E}\{\sigma + m[(\dfrac{\sigma}{\sigma_{ys}})^{n} - 1]\sigma_{ys}\} & , \quad \sigma > \sigma_{ys} \end{cases} \qquad (6)$$

in which m and n are the strain hardening coefficients. Referring to Figure 1, the strain energy density function at a given point, say p, may be computed as

$$\frac{dW}{dV} = \int_0^{\varepsilon} \sigma d\varepsilon \qquad (7)$$

Making use of equation (6), equation (7) may be integrated to yield

$$\frac{dW}{dV} = \frac{1}{E}\left[\frac{1}{2}\sigma^2 + \frac{mn}{n+1}\frac{\sigma^{n+1}}{\sigma_{ys}^{n-1}}\right] \qquad (8)$$

The critical value $(dW/dV)_c$ may be found by simply letting σ equal to σ_{ue}. From equations (2) and (8) the available energy density at failure can also be obtained

$$\left(\frac{dW}{dV}\right)_c^* = \frac{\sigma_{ue}^2}{2E}\left[1 + nm\left(\frac{\sigma_{ue}}{\sigma_{ys}}\right)^{n-1}\right] \qquad (9)$$

Once, σ_{ys} and σ_{ue} are known, appropriate values of m and n for a given material may be selected to generate a complete stress and strain curve from which $(dW/dV)_c$ or $(dW/dV)_c^*$ can be obtained.

2.3 Fatigue Crack Growth Properties

If the loads are applied repeatedly at a value considerably lower* than the yield strength, failure will eventually take place after many cycles of repeated loading. The LEFM approach [1] assumes that the rate of crack growth da/dN is related to the change in stress intensity factor ΔK, i.e.,

---

*The stress amplitude is usually taken as 50% of the yield strength while the mean stress level can be zero or non-zero.

$$\frac{da}{dN} = A(\Delta K)^M \qquad (10)$$

where A and M are empirically determined parameters, they cannot be regarded as material constants because they are sensitive to changes to specimen geometry and size [9,10]. As ΔK is determined from the theory of elasticity, there are conceptual difficulties associated with the application of equation (10). Fatigue is a process where damage is accumulated over many cycles of loading while elasticity considers only processes that are reversible involving no energy dissipation. For this reason, da/dN should be estimated from quantities that account for damage accumulation.

The strain energy density criterion [4-7] discussed earlier applies equally well to fatigue by assuming that failure of an uniaxial specimen subjected to cyclic loading $\sigma(t)$ in Figure 4 will occur when the strain energy density function after many cycles of accumulation reaches a critical value, say C, i.e.,

$$\sum_{j=1}^{\Delta N} \left(\frac{\Delta W}{\Delta V}\right)_j = C \qquad (11)$$

A weighted average $\overline{\Delta W/\Delta V}$ can thus be obtained such that

$$\overline{\frac{\Delta W}{\Delta V}} \cdot \Delta N = C \qquad (12)$$

Referring to Figure 4, the variation of $\overline{\Delta W/\Delta V}$ when the distance r

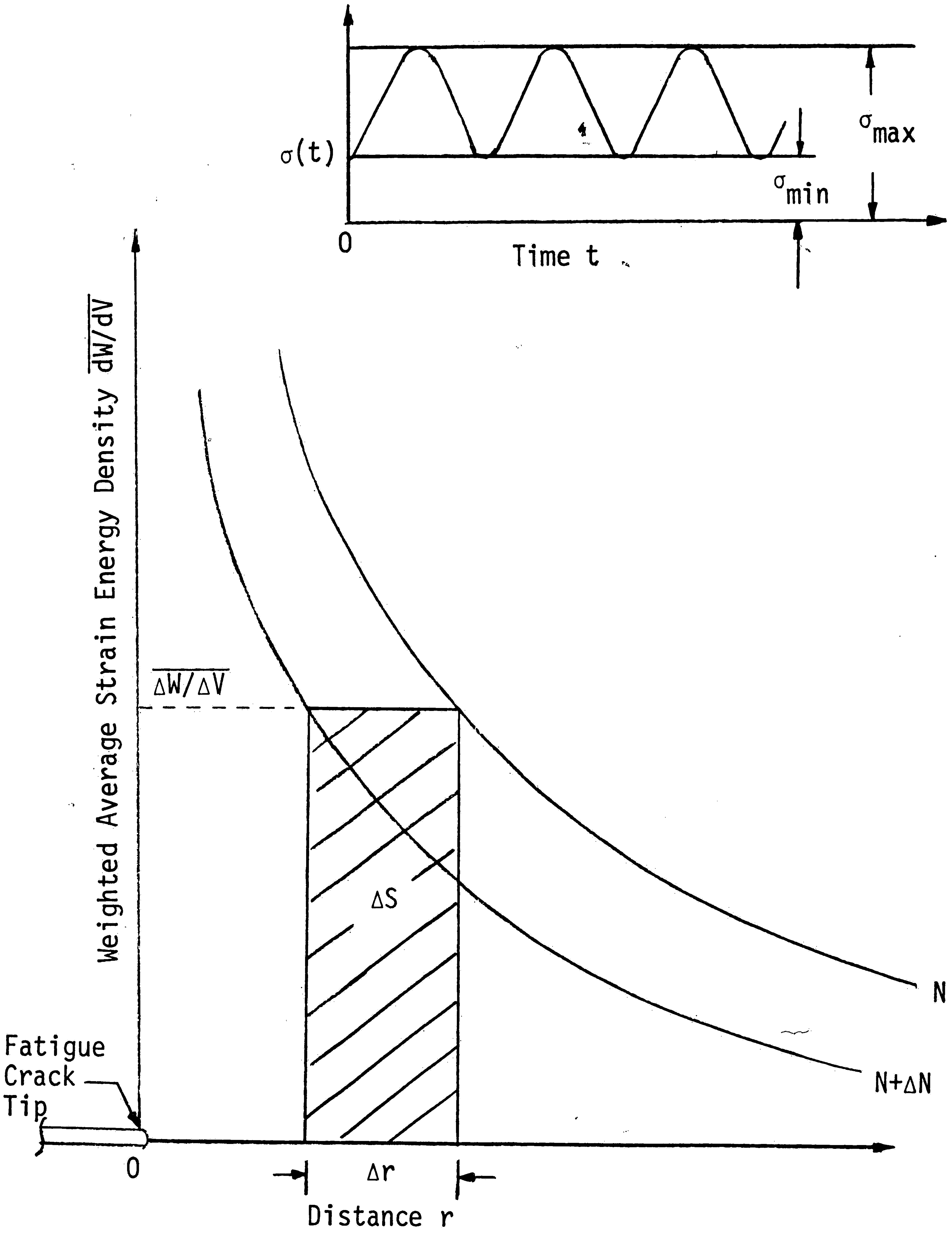

Figure 4. Schematic Of Permanent Change In The Strain Energy Density Factor.

ahead of a fatigue crack is shown. Because of the irreversible nature of the fatigue process, the $\overline{\Delta W/\Delta V}$ versus N curve will not coincide with that after ΔN number of load cycles. There prevails an incremental change in the strain energy density factor ΔS which is the area

$$\Delta S = \overline{\frac{\Delta W}{\Delta V}} \cdot \Delta r \tag{13}$$

Combining equations (12) and (13) gives

$$\frac{\Delta r}{\Delta N} = B(\Delta S) \tag{14}$$

in which B is the reciprocal of C obtained from the cyclic uniaxial test, i.e.,

$$B = \frac{1}{C} \tag{15}$$

It can also be deduced from a fatigue crack growth test. By taking logarithm of both sides of equation (14), B is the y-intercept on a log $(\Delta r/\Delta N)$ versus $\log(\Delta S)$ plot (Figure 5) with a 45 degree slope line. Indeed, the work in [11,12] shows that the 45 degree-line correlates well with fatigue data on metals. What should be emphasized is that ΔS must now be computed from the theory of plasticity or any other theories that includes the mechanism of energy dissipation.

The unique feature of the strain energy density criterion is that only one parameter C or B is required to characterize the

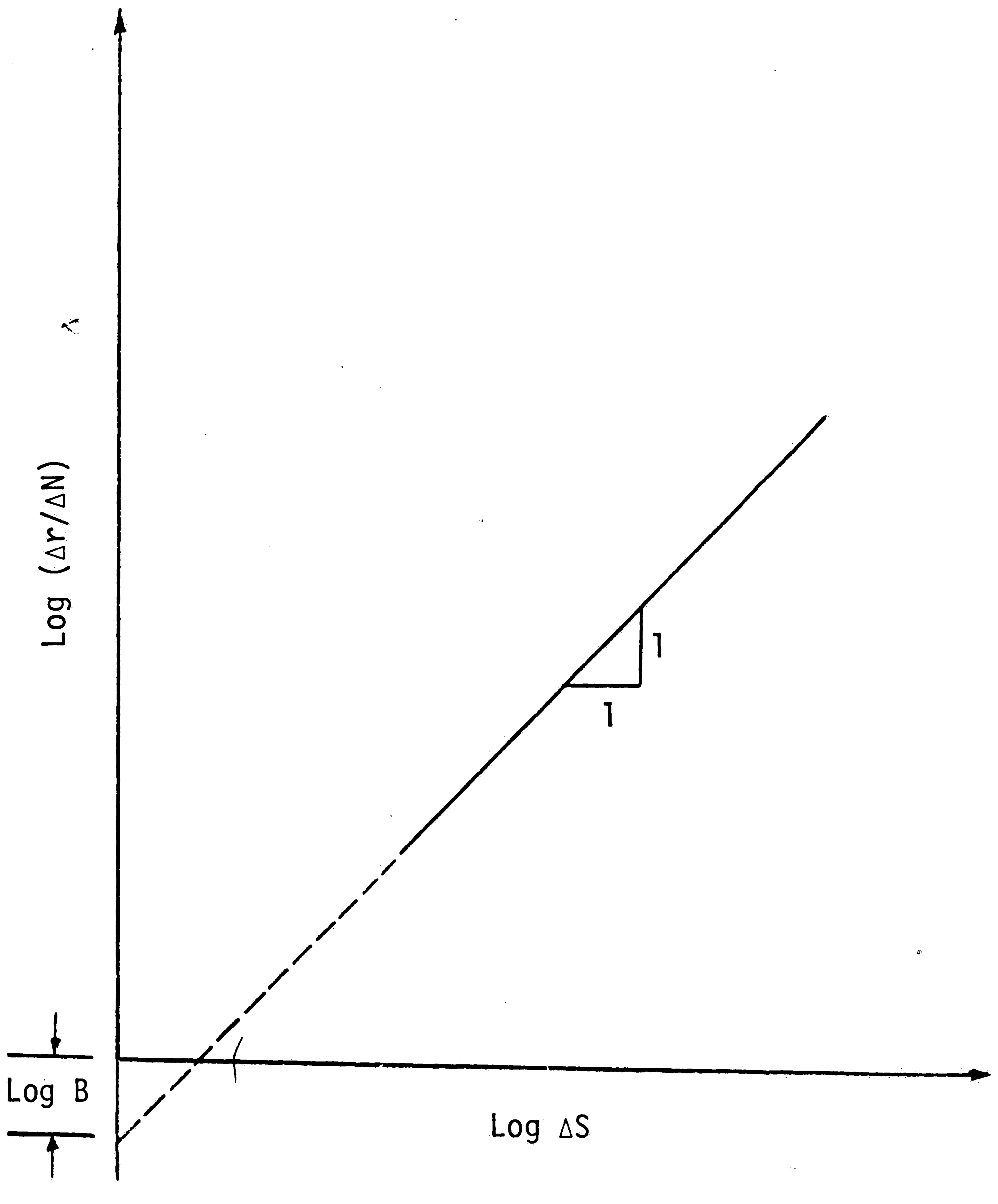

Figure 5. Fatigue Crack Growth Versus Change Of Strain Energy Density Factor.

fatigue property of a material. The parameter C obtained from a cyclic uniaxial test is simply the reciprocal of B that can b evaluated independently from a fatigue crack growth test. A means of checking the validity of the model is also provided.

III. DEVELOPMENT OF MATERIAL DATABASE

The concept of a centralized material database is not new [8]. Depending on the objective of the user, the contents of one database may differ widely from another. Such information will not normally be made available to the general public, mainly because database development requires a great deal of efforts in addition to know how. The ease with which useful results can be made available quickly becomes a measure of the effectiveness of the program. In what follows, the "Fracture Analysis Material Evaluation Database (FAMED)" program will be developed. It has the capability for determining the integrity of simple structures with a crack. Material behavior owing to changes in geometry and size, loading and material type can be automatically adjusted. Only metal alloys are considered although the same procedure applied to other materials.

3.1 Preliminary Information

The three commonly used metals are aluminum, steel and titanium. Their basic mechanical and fracture properties are given in Table 1 in which material 1, 2 and 3 refer respectively to aluminum, steel and titanium. Fatigue Load will be defined in terms of the stress amplitued $\Delta\sigma$ and mean stress $\bar{\sigma}$

$$\Delta\sigma = \frac{1}{2}(\sigma_{max} - \sigma_{min}) \quad ; \quad \bar{\sigma} = \frac{1}{2}(\sigma_{max} + \sigma_{min}) \qquad (16)$$

Table 1. Mechanical and Fracture Properties of Aluminum, Steel and Titanium

Material Properties / Material Type	Young's Modulus E(MPa)	ν Poisson's Ratio	σ_{ys} (MPa)	σ_{ul} (MPa)	ε_{ys} (cm/cm)	ε_{ul} (cm/cm)	$(\frac{dW}{dV})_c$ (MPa)	S_c (KN/m)	K_{1c} (MPa$\sqrt{m}$)
1	1.66×10^5	0.33	413.69	1585.81	2×10^{-3}	4.08×10^{-2}	49.82	19.815	222.54
2	2.07×10^5	0.25	517.11	1378.97	2.5×10^{-3}	1.34×10^{-2}	12.32	13.485	183.60
3	2.50×10^5	0.321	620.53	1172.12	3×10^{-3}	7.04×10^{-3}	4.7	9.104	150.79

in which σ_{max} and σ_{min} are respectively the maximum and minimum applied stress indicated in Figure 4. Refer to Table 2 for the three combinations referred to as type I, II and III. Variations in specimen geometry and crack shape are also considered. They consist of a solid circular cylinder with a penny-shaped crack, rectangular plate with an edge crack and a hollowed cylinder with an edge crack at the inner boundary. A total of nine cases A, B,---, I are obtained. The dimensions of the three specimens are selected such that they have the same three corresponding V/A ratios. Refer to Figures 6 to 8 inclusive for details.

3.2 Data Code System

Based on the strain energy density fatigue model described in Section 2.3 and the procedure for obtaining ΔS in [13], the crack growth data for each load type in Table 2 can be obtained. For the case of a steel circular cylinder of specimen type A (Figure 6) subjected to load type I (Table 2), Table 3 summarizes the crack growth data for 5,700 load cycles in increment of 300 cycles. The corresponding values of the strain energy density factor S are also given which will be used subsequently for constructing the crack growth resistance curve a procedure that will be used to generate additional data for evaluating loading rate and specimen size effects. With three different variations of specimen type, material and fatigue loading, there results a total of 27 combina-

Table 2. Fatigue Load Type I, II and III

Loading Type	$\bar{\sigma}$(MPa) $= \frac{1}{2}(\sigma_{max} + \sigma_{min})$	$\Delta\sigma$(MPa) $= \frac{1}{2}(\sigma_{max} - \sigma_{min})$
I	206.9 ($\sigma_{max} = 48$; $\sigma_{min} = 12$)	124.1
II	258.1 ($\sigma_{max} = 60$; $\sigma_{min} = 15$)	155.2
III	284.5 ($\sigma_{max} = 65.9$; $\sigma_{min} = 16.5$)	170.7

Specimen Type	Radius b(cm)	Length L(cm)	$\frac{V}{A}$ (cm)
A	12.7	50.8	5.08
B	19.05	76.2	7.62
C	25.4	101.6	10.16

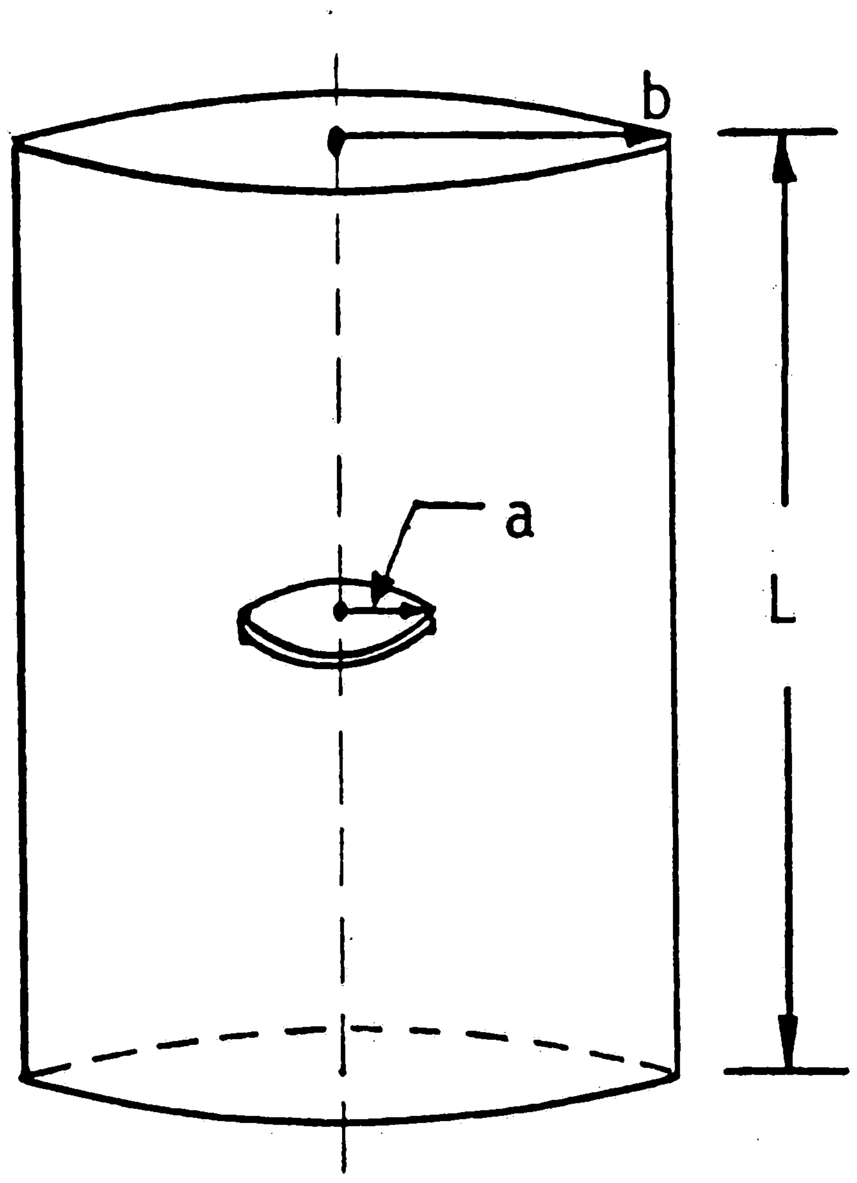

Figure 6. Solid Cylinder With Penny-Shaped Crack

Specimen Type	Thickness h(cm)	Width 2b(cm)	Height L(cm)	$\frac{V}{A}$(cm)
D	11.684	116.84	233.68	5.08
E	17.526	175.26	350.52	7.62
F	23.368	233.68	467.36	10.16

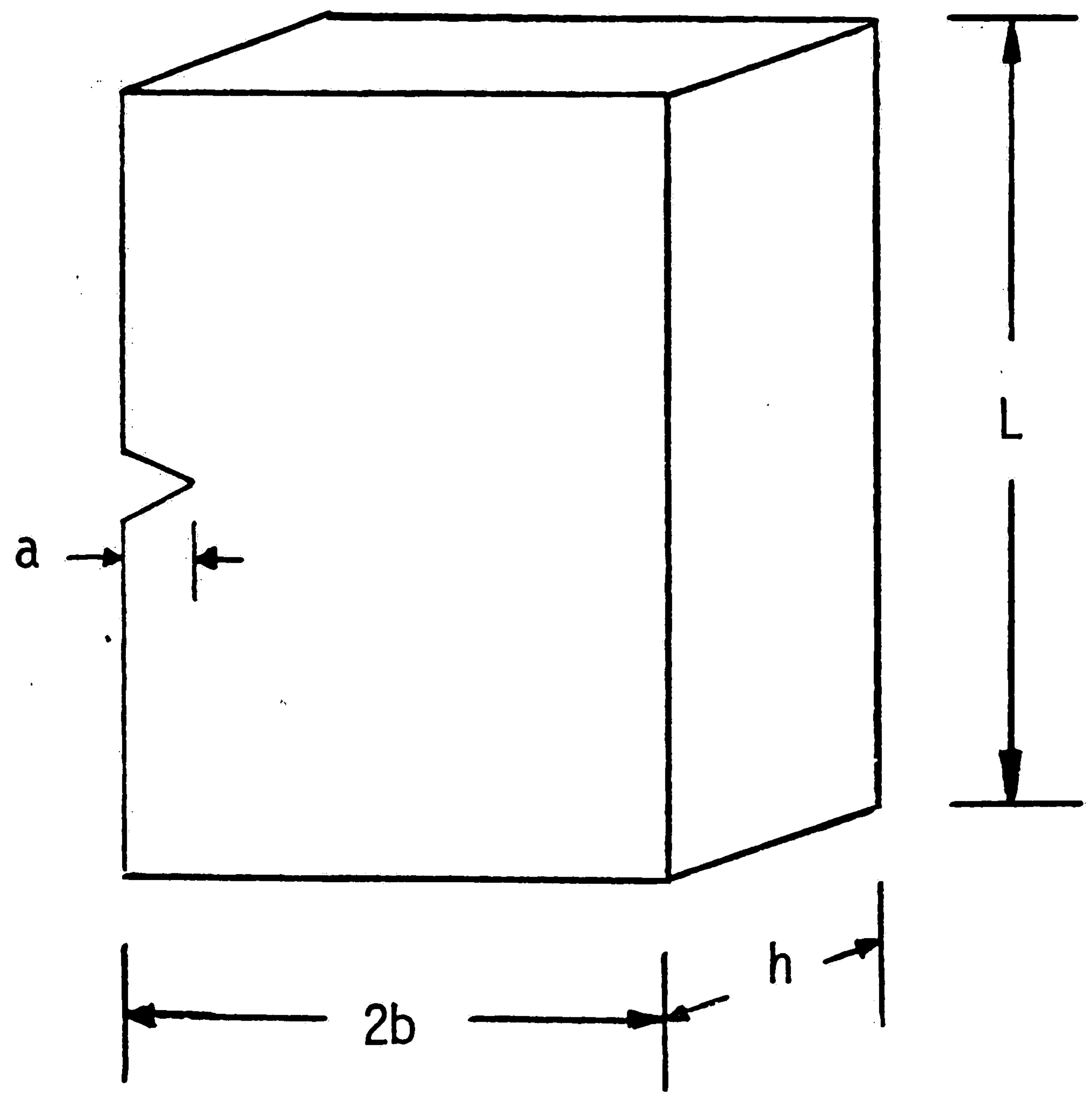

Figure 7. Plate With Edge Crack

Specimen Type	Inner Radius c(cm)	Outer Radius b(cm)	Length L(cm)	$\frac{V}{A}$(cm)
G	4.6	9.2	36.8	5.08
H	6.9	13.8	55.2	7.62
I	9.2	18.4	73.6	10.16

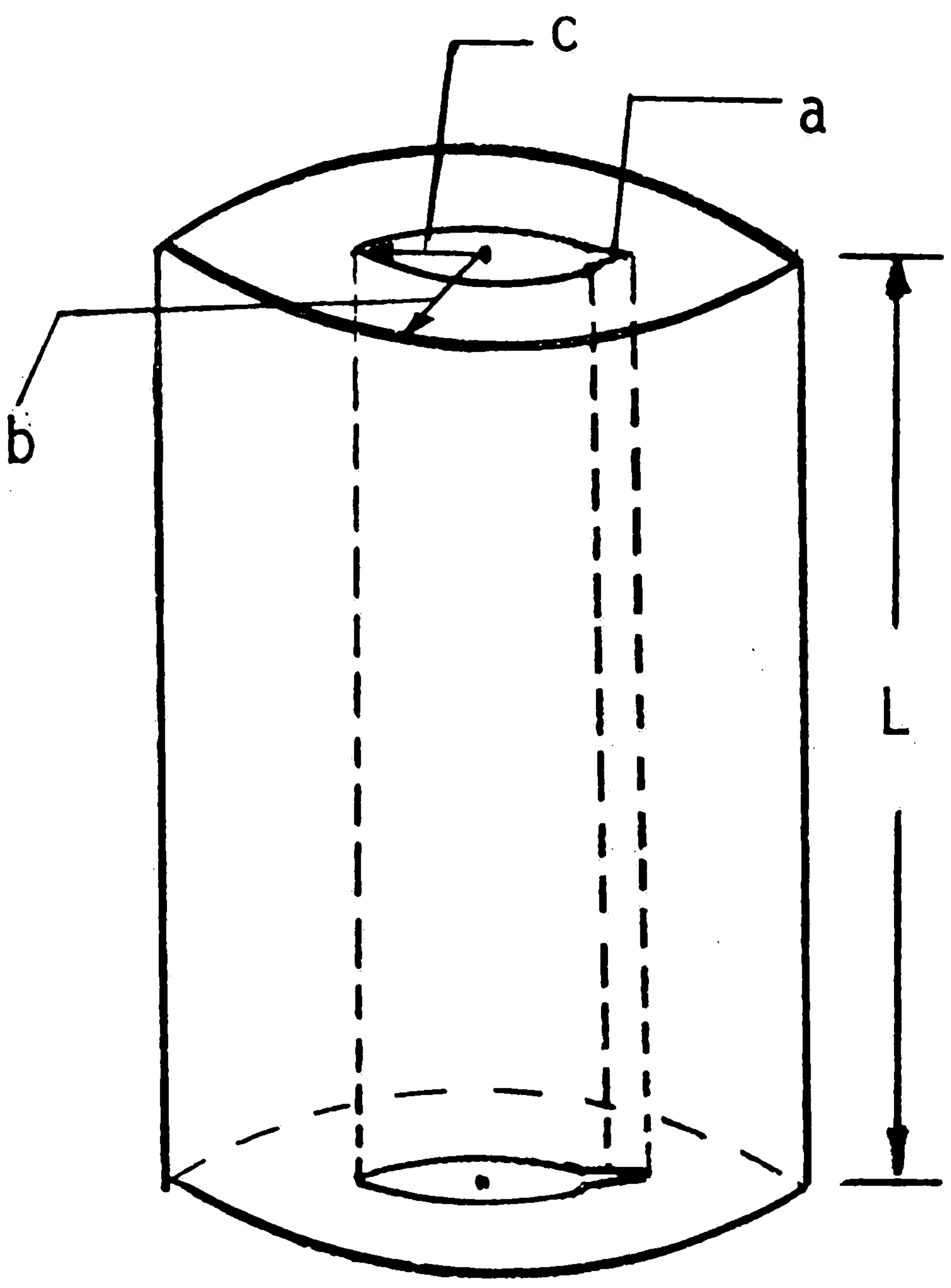

Figure 8. Hollow Cylinder Arch Edge Crack

Table 3. Fatigue Crack Growth Data For Material 2, Specimen A and Load Type I

a(cm)	N(Cycles)	$\Delta a/\Delta N(x10^{-4})$	S(kN/m)
2.540	0	0	0
2.604	300	2,133	1.149
2.675	600	2,367	1.277
2.758	900	2,767	1.435
2.859	1200	3,367	1.630
2.983	1500	4,133	1.866
3.128	1800	4,833	2.127
3.296	2100	5,600	2.429
3.491	2400	6,500	2.780
3.719	2700	7,600	3.190
3.986	3000	8,900	3.671
4.298	3300	10,400	4.233
4.663	3600	12,170	4.890
5.090	3900	14,230	5.723
5.583	4200	16,430	6.610
6.154	4500	19,030	7.746
6.812	4800	21,930	8.884
7.566	5100	25,130	10.391
8.421	5400	28,500	11.845
9.382	5700	32,030	13.383
9.439	5705	114,000	13.485

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8.421	5400	28,500	11.845
9.382	5700	32,030	13.383
9.439	5705	114,000	13.485

tions. That is for the solid cylinder configuration in Figure 6, a total of 27 critical crack sizes are found, Table 4. This number will increase to 81 if the two other specimen configurations in Figures 7 and 8 are also considered. Because of the enormous increase in accumulated data as more combinations of loading, specimen geometry and material are included, a code system needs to be developed.

Data storage in the FAMED program will be referred to by a four digit code*. Letters and numbers will be assigned consecutively to denote the specimen type, material , load and flaw size including location in the order stated. For example 1IAa refers to material 1, load type I, specimen A and flaw size a. Specimen A as defined in Figure 6 is a solid cylinder with radius 12.7 cm and L = 50.8 cm giving V/A = 5.08 cm. Material 1 is aluminum and load type I pertains to $\bar{\sigma}$ = 206.9 MPa and $\Delta\sigma$ = 124.1 MPa (Table 2). In this way, each one of the 27 critical crack size in Table 4 can be identified by the code numbers 1IAa, 2IAa,---,3IIICa. Additional data may be added and they can be coded as 1IDa, 2IDa,---3IIIFa. Specimen type D is defined in Figure 7 while the other three digits refer to material, load and flaw type as before.

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*An additional digit may be added for flaw location such as o would denote a flaw at center of specimen.

Table 4. Critical Crack Size For Different Combination Of Fatigue Load, Material And Specimen Type.

Specimen Type	Material Type	Critical Crack Size a_c (cm)		
		Load Type I	Load Type II	Load Type III
A	1	10.375(cm)	9.215	8.456
	2	9.439	8.020	6.817
	3	8.753	7.187	5.384
B	1	11.263	9.912	8.984
	2	10.137	8.797	7.431
	3	9.595	7.893	6.244
C	1	12.000	10.643	9.263
	2	10.634	9.437	8.095
	3	10.312	8.606	6.954

3.3 Crack Growth Resistance Curves

When crack growth is accompanied by yielding, the load versus displacement relations for a cracked specimen or the crack length versus number of load cycle relations become highly nonlinear and are not readily adaptable for use in design. The objective of constructing the crack growth resistance curves (R-curves) therefore is to linearize the nonlinear fracture data. Criteria such as the crack opening displacement [14] and J-integral [15] approach are not useful since their relations with crack growth remain nonlinear. Such an exercise defeats the very purpose of constructing R-curves.

Figures 9(a) and (b) illustrate schematically that plots of ΔS versus Δa could be parallel lines if the specimen size is altered. The larger or thicker specimens corresponding to a higher V/A ratio* would behave more brittle and rapid fracture would occur with little or no slow crack growth, Figure 9(a). The precise amount of slow crack growth Δa prior to incipient failure is determined from the intersections of the S_c = constant line with the parallel dS/da = constant lines. Failure by plastic collapse would result if the specimen size is reduced so small that yielding be-

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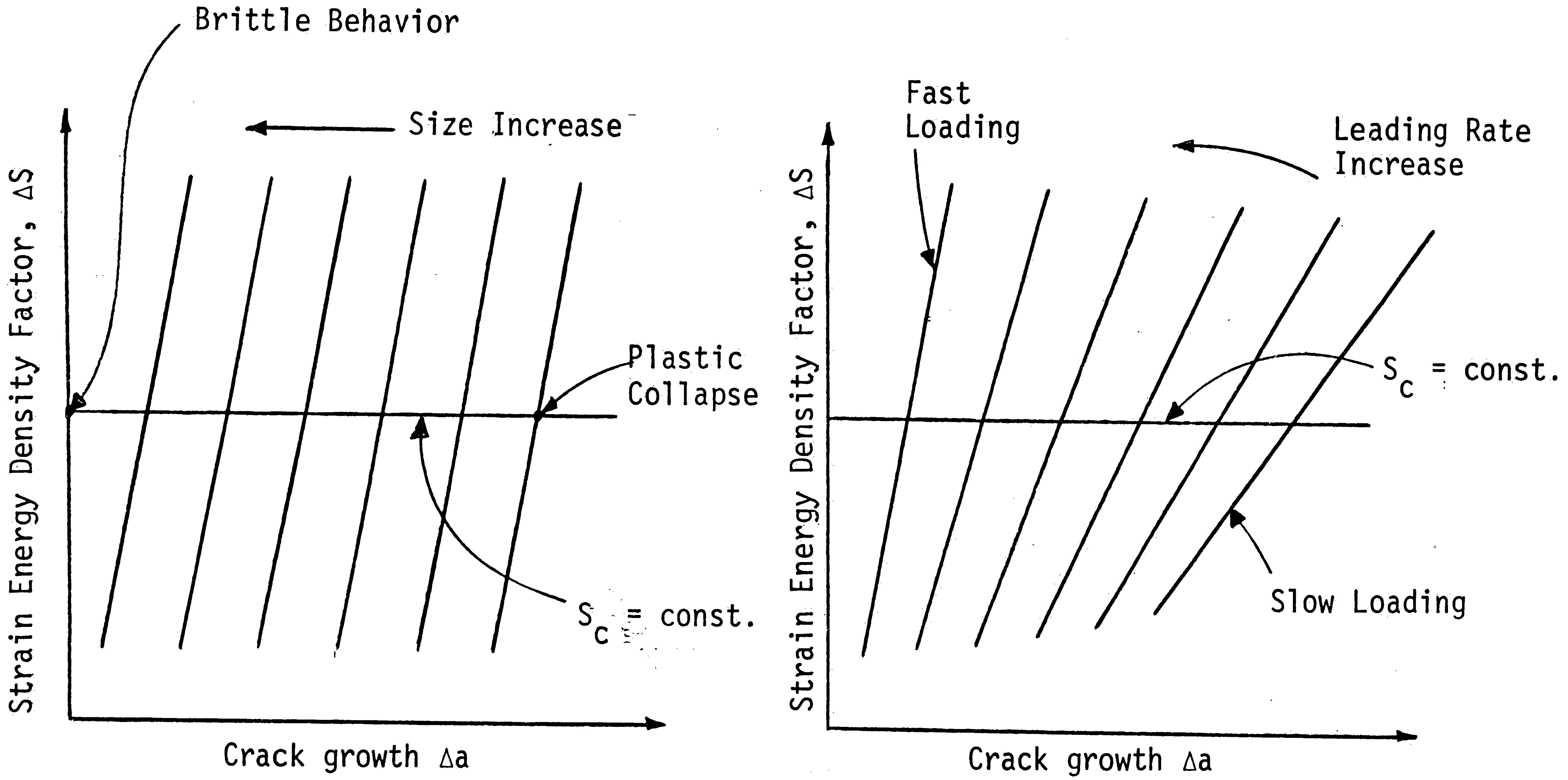
*It is more expedient to express size effect in terms of V/A rather than thickness or cylinder radius so that the brittle and/or ductile behavior of specimens with different geometries can be compared on equal footing.



(a) Size Effect (b) Loading Rate Effect

Figure 9. Crack Growth Resistance Curves For Change In Specimen Size And Loading Rate

gins to dominate. Loading rate also has an influence on slow crack growth behavior. Figure 9(b) shows that as the loading rate is increased the dS/da = constant lines tend to rotate in a counterclockwise direction. Crack can grow in a stable fashion for a long period of time if the loading rate is slowed down. This corresponds to the phenomenon of creep.

More specifically, Figure 10 displays the ΔS versus Δa plots for a cylindrical steel bar specimen subjected to load type I. Three parallel lines are obtained that correspond to V/A = 5.08, 7.62 and 10.16 cm. The amount of slow crack growth can be obtained from the interactions of the S_c = 13.485 KN/m constant line. Similarly, the cylindrical specimen V/A ratio may be fixed at V/A = 5.08 cm and the material is assumed to be steel. Three dS/da = constant lines are again obtained. It is seen from Figure 11 that the lines rotate counterclockwise as σ and $\Delta\sigma$ are increased. Fatigue slow crack growth is therefore entranced by lowering $\bar{\sigma}$ and $\Delta\sigma$. The material type may also be varied as it is done in Figure 12. The material with the highest S_c = 19.815 KN/m being the aluminun attains the largest crack growth Δa. Next in line is steel and titanium comes in last with S_c = 9.104 KN/m. The material possesses the highest toughness value in this case also has the longest subcritical crack growth period.

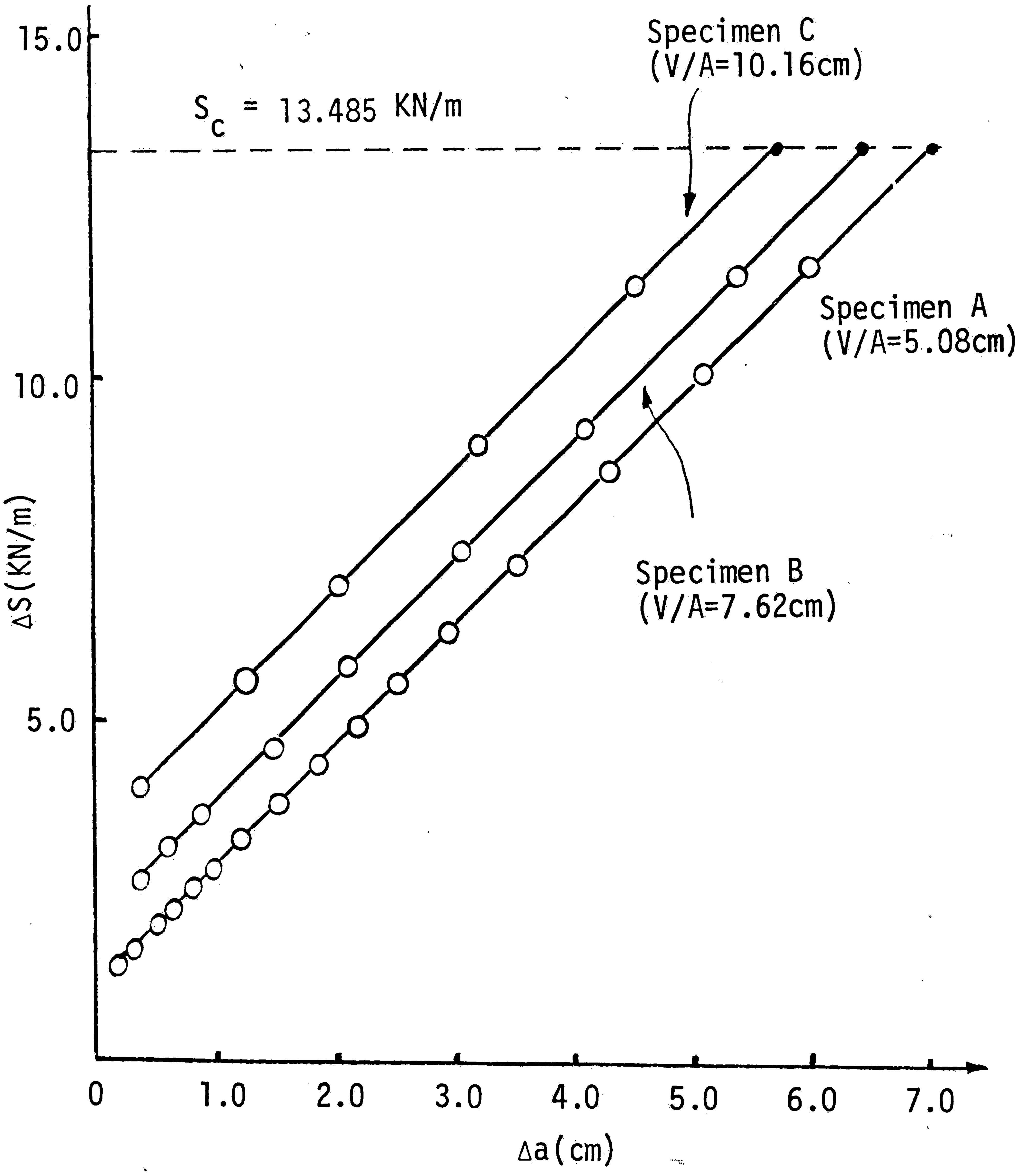


Figure 10. Crack Growth Resistance Curves For Load Type I

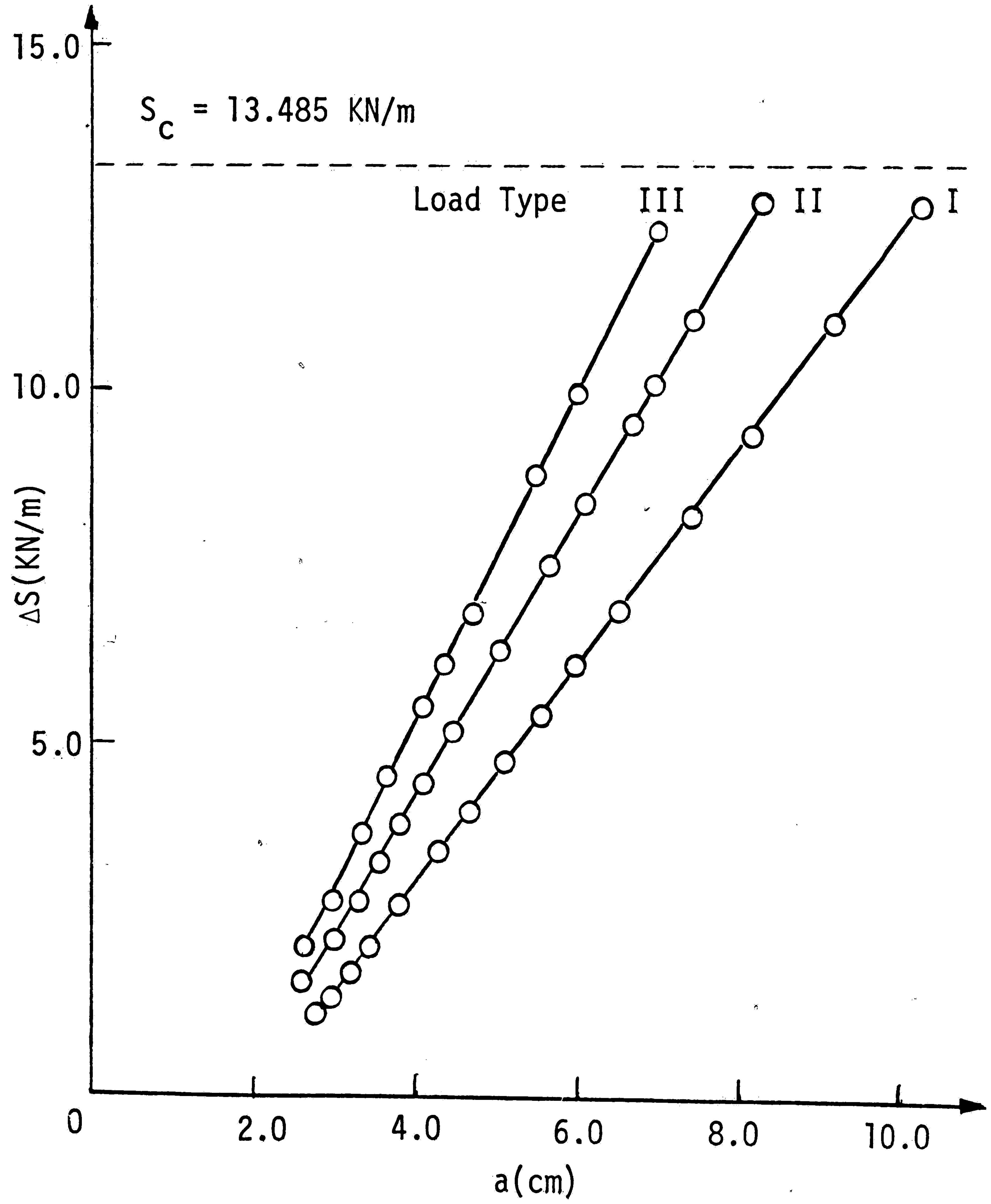


Figure 11. Crack Growth Resistance Curves For Load Type I, II and III.

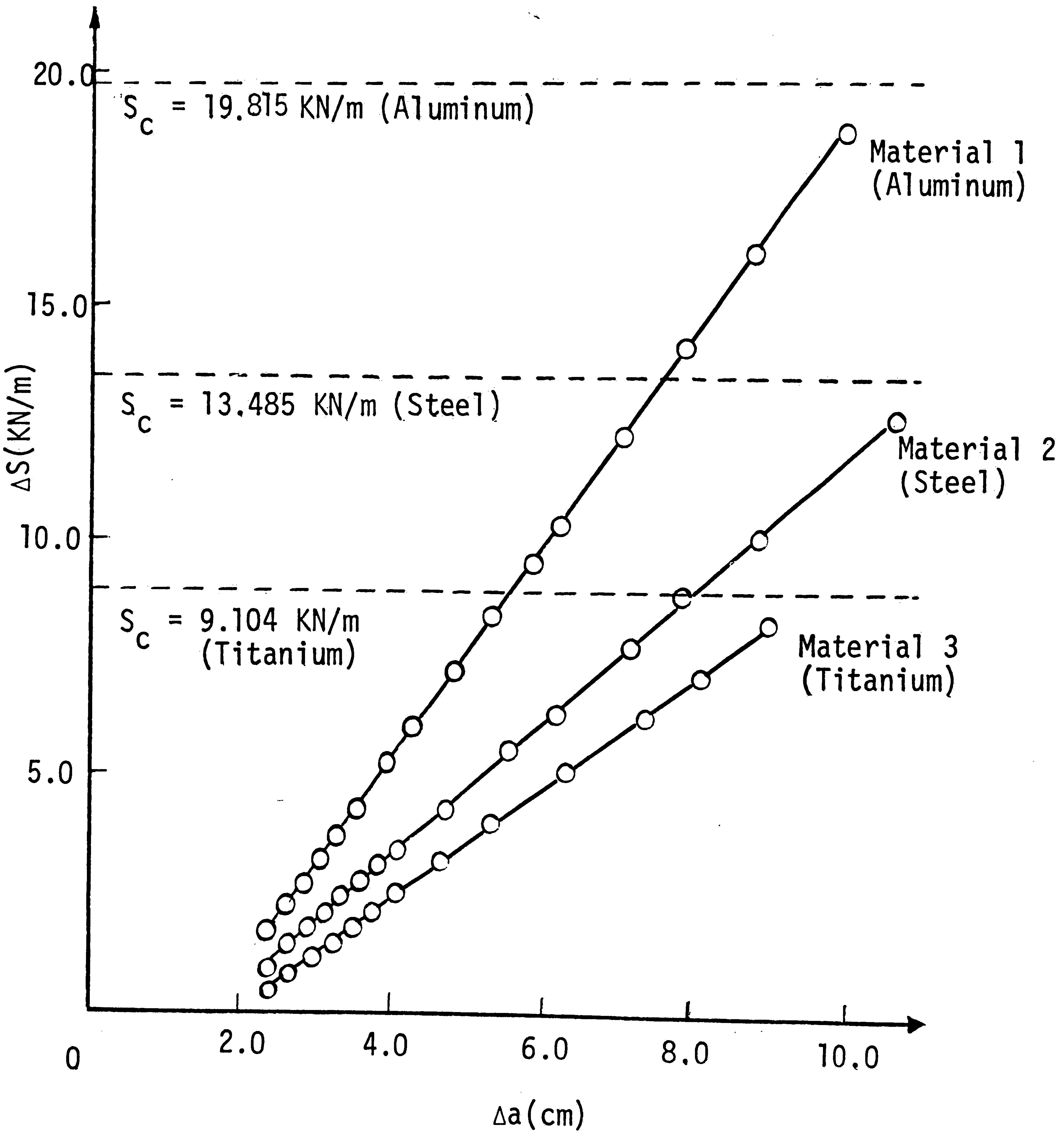


Figure 12. Crack Growth Resistance Curves For Material 1, 2 and 3, specimen A and Load Type I.

3.4 Interpolation of Data

Of particular interest is the critical crack size at which rapid fracture occurs. A situation that should be pre-determined if possible and avoided. For a circular cylinder with a initial crack radius of 2.54 cm, Figure 10 gives three values of a_c corresponding to V/A = 5.08, 7.62 and 10.16 cm. Hence, a plot of a_c versus V/A may be constructed such that other combinations of a_c and V/A may be obtained by interpolation or simply graphically as given in Figure 13. This, of course, can be accomplished by a subroutine in the FAMED program.

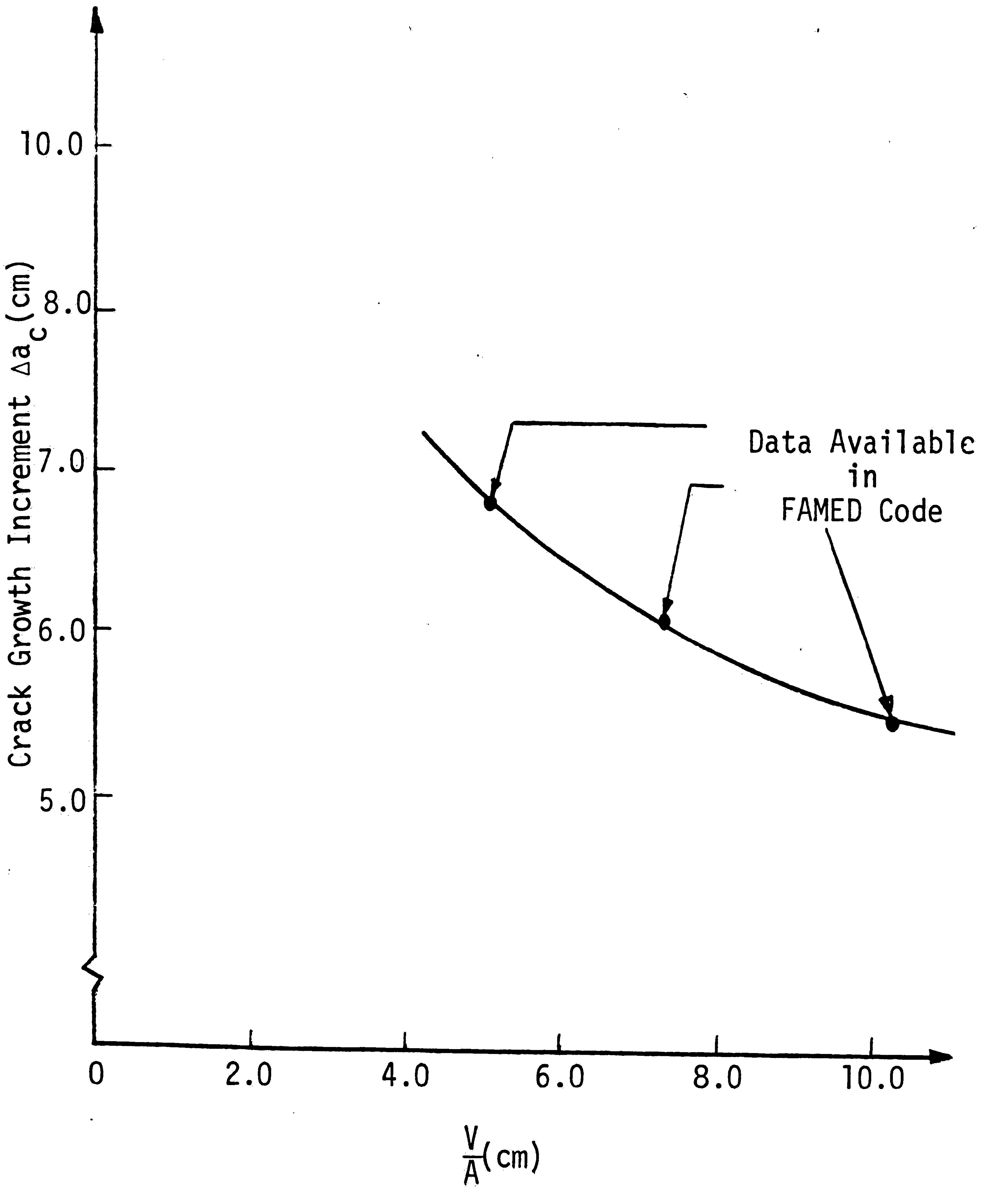


Figure 13. Variations of Δa_c With V/A For Material 2 (Steel) and Load Type I.

IV. FRACTURE ANALYSIS MATERIAL EVALUATION DATABASE (FAMED) PROGRAM

This program [16] is developed for those users who may not be familiar with fracture mechanics involving the nonlinear analysis of material behavior. Such a knowledge is beyond the capability of most engineers in the industry. A user friendly program would therefore enable the ordinary engineers to design more sophisticated components that they otherwise should not have been able to do so. As modern technology advances more and more rapidly, such a trend is the future.

4.1 Flow Chart

A flow chart of the FAMED code is shown in Figure 14. The user must first select the material type according to the number 1, 2 and 3. The mean stress $\bar{\sigma}$ and stress amplitude $\Delta\sigma$ must then be decided so that a Roman numeral between I to III is chosen. If the fatigue load falls outside of I, II and III, the user may obtain three answers and find the answer by interpolation. The specimen type and size is designated by the letters A, B,---,I. Three different values of V/A are available for each specimen configuration. Again, an interpolation scheme must be used if the V/A value does not coincide with those listed. The flaw size and location must then be specified so that a four digit code such as A1Ia, A2Ia, etc. can be fed in the FAMED program. The critical flaw size a_c and number of cycles N_f to final fracture are then obtained as output.

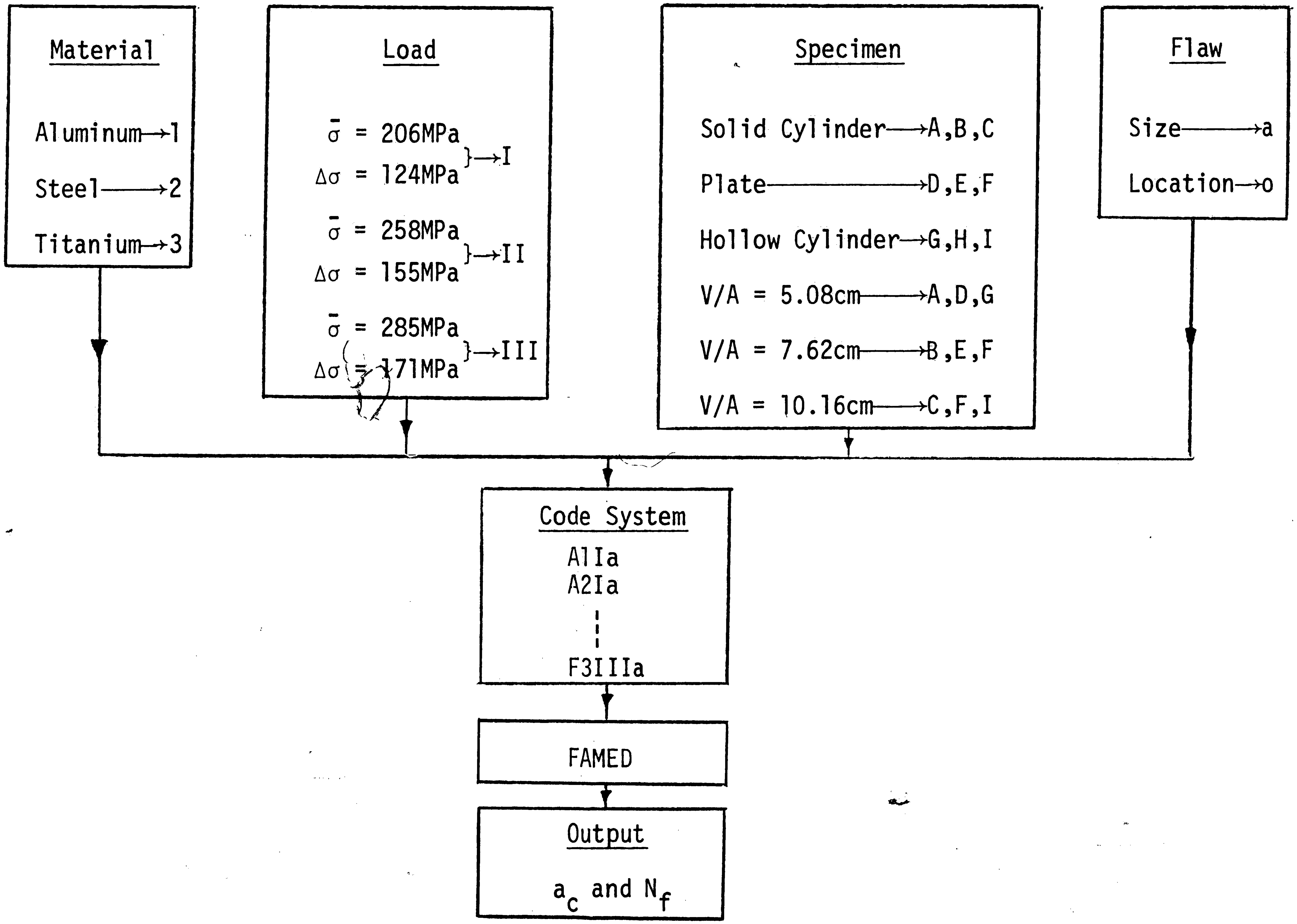


Figure 14. Flaw Chart Of FAMED For Evaluating Critical Flaw Size And Fatigue Life.

4.2 User Procedure

To use the FAMED code, follow the steps indicated in the flow chart, Figure 14. Refer to the Appendix in Section VII for the computer program.

Step 1 - Material selection.

(1) If user chooses aluminum, indicate number 1
(2) If user chooses steel, indicate number 2
(3) If user chooses titanium, indicate number 3

Suppose that steel is chosen, i.e., type 2, the user's manual will furnish the following information as in Table 1:

$\sigma_{ys} = 517.11$ MPa ; $\sigma_{ue} = 1378.9$ MPa

$\varepsilon_{ys} = 2.50\times10^{-3}$ cm/cm ; $\varepsilon_{ue} = 1.34\times10^{-2}$ cm/cm

Then the first digit in the code is chosen as 2, i.e., 2xxx.

Step 2 - Fatigue Load

The choices available to the user are shown in the flow chart (or Table 2). Again, these will be given in the user's manual.

Suppose that the user selects load type I referring to

$\overline{\sigma} = 206.9$ MPa ; $\Delta\sigma = 1241.$ MPa

the second digit in the code is then decided, i.e., 2Ixx.

Step 3 - Specimen Configuration

For a solid cylinder with length L = 50.8 cm and radius b = 12.7 cm, the V/A ratio is 5.08 cm. This corresponds to specimen type A, Figure 6. Determined is the third digit in the code number: 2IAX.

Step 4 - Initial Flaw Size and Location

Suppose that the initial flaw size is 2.54 cm and is located at the center of the specimen. Then, the fourth digit a will be assigned. This completes the four digit code 2IAa.

Step 5 - Input Code Number

The code number 2IAa is punched into the FAMED program.

Step 6 - Request for Output

The output of a_c = 6.812 cm and N_f = 4,800 cycles will then be obtained as they are shown in Table 3. Except that the information will be stored in the computer and can be made available on command.

4.3 Additional Subroutine

If the user's input data does not coincide precisely with those in Steps 1 to 4 or those stored in the FAMED program, then at least three outputs on a_c and N_f should be obtained such that the actual answer can be obtained by interpolation as discussed in Section 3.4. Additional subroutines may be developed by the user so that the procedure can be done automatically by the computer.

V. NON-DESTRUCTIVE EVALUATION

One of the main objectives of fracture mechanics is to determine the onset of unstable fracture in terms of a critical crack length a_c so that such a condition can be prevented in service. This can be accomplished by periodic inspection of the structural component in question. Such a methodology is known as "fracture control".

Figure 15 shows a schematic of crack length versus number of load cycle. As the crack grows very slowly initially, the number of cycles N_s corresponding to a certain growth rate $\Delta a/\Delta N$ should be so as to establish the inspection interval. The number of cycles between the useful and fatigue life may be regarded as the safety margin. The fracture mechanics discipline may thus be applied to find a_f, N_f, and N_s with a predetermined margin of safety. The implementation of fracture control in practice requires the application of nondestructive testing [17-19]. An estimate of the remaining life of the structural component is needed. Depending on the environment and available personnel, recommendation on the use of a particular technique can then be made.

5.1 Commercially Available Non-Destructive Testing Devices

Non-destructive testing is still an art in that only the more experienced individual can reliably detect defects in a given structure. The reliability of detection depends on many variables such as the flaw size, flaw location, material, etc. A brief description of some of the common methods will be given.

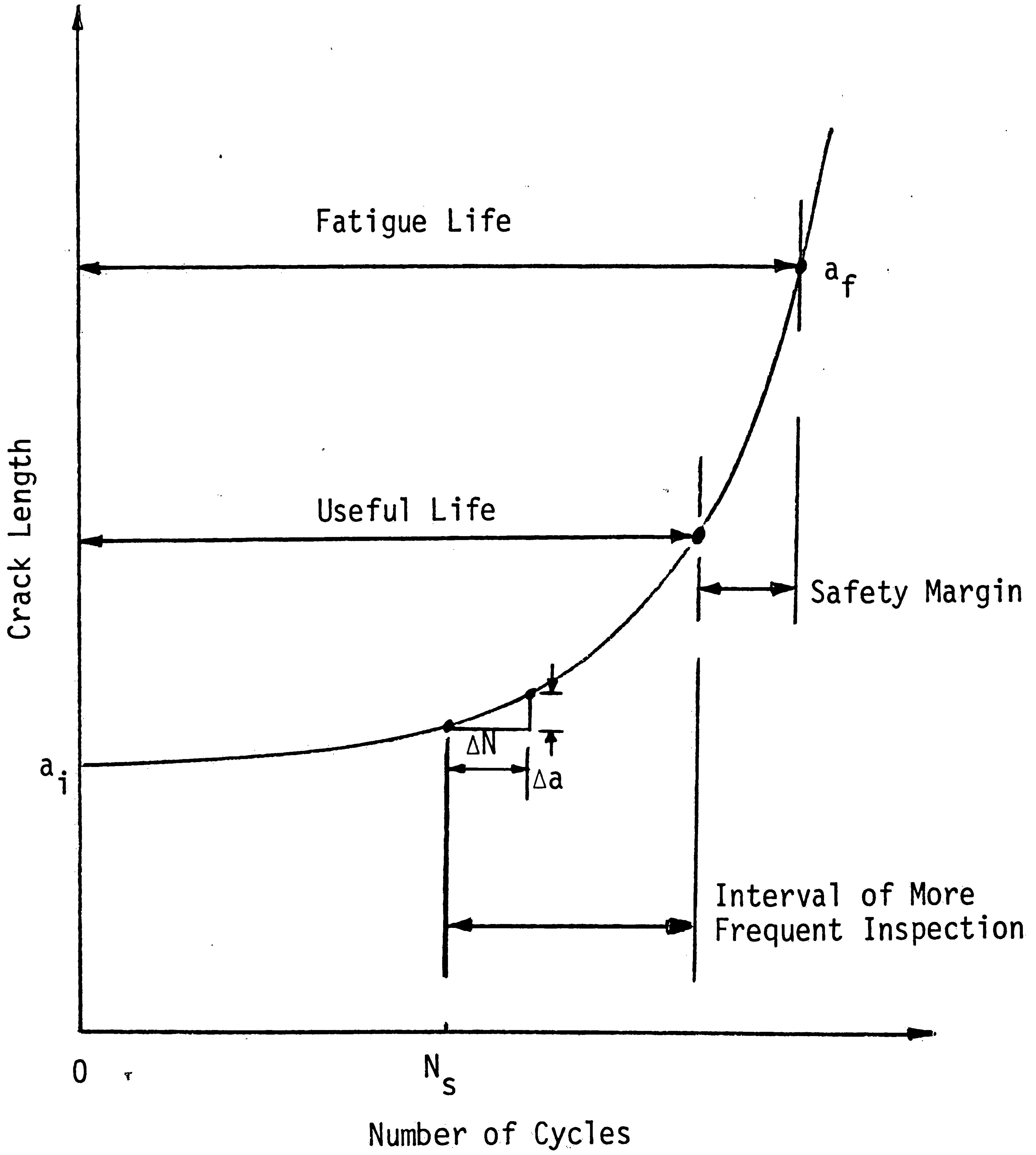


Figure 15. Crack Length Versus Number of Cycles.

5.1.1 Dye Penetrant

This method applies to surface flaws in metals, ceramics, and materials that should be non-porous. It is generally used to locate cracks in welds, castings and machine parts after grinding, etc. It is relatively inexpensive and can be readily administered. Inspection can be made visually. No information, however, could be obtained on flaw depth.

5.1.2 Magnetic Particles

It applies to ferromagnetic materials where the fine magnetic particles or powder can reveal the presence of flaws or surface cracks. The free surface or opening of the crack acts like a pair of magnets as a result of flux leakage. The defective surface of course, must be assessable and reasonably clean so as to achieve good resolution. Grinding or machining of the surface becomes necessary if the material is too rough.

5.1.3 Eddy Current

A relatively inexpensive means of detecting embedded cracks is by correlating the change in current as a result of alteration of coil inductance due to the presence of cracks. This method is widely used in the nuclear industry.

5.1.4 Ultrasonics

High frequency wave is transmitted into the material by a transducer made from piezo-electric crystals. Waves are reflected when encountering a surface boundary and/or a crack and monitored on the oscilloscope. Distance between the first pulse and reflection gives the location of the crack. The crack size can also be estimated from the wave reflection pattern. Ultrasonic measurements usually underestimate the crack size because the adjoining surfaces may be closed.

5.1.5 X-Ray

X-ray is one of the most widely used techniques in nondestructive testing. The intensity of radiation is interrupted by defects in the material. The nonuniform absorption of radiation appears on the film. X-ray wavelength is in the order of one angstrom or 10^{-8}cm. It becomes tedius if detection were to be performed over a large area.

5.1.6 Acoustic Emission

This technique relies on a high signal-to-noise ratio. It assumes that the acoustic energy released is proportional to the size of defect created during loading. It can be used to monitor the creation of flaws in a full size structure that is in service. The location of a flaw can be determined by using several sensors positioned in a trinagular pattern such that the loci of failure role can be found.

5.2 Flaw Sensitivity In Material

Cracks in the higher strength materials are usually more difficult to detect because the adjoining surfaces can be extremely tight. Detection becomes impossible when the crack opening is closed and of the same order of magnitude as the grain boundary thickness. According to linear elastic fracture mechanics, the crack opening governed by the radius of curvature ρ in relation to crack length 2a centered in a uniformly plate by the relation

$$a = \frac{1}{4}\left(\frac{\sigma_m}{\sigma}\right)^2 \rho \qquad (17)$$

where σ is the applied stress and σ_m the local crack tip stress. Since the tightness of the crack measured by ρ is directly proportional to a, cracks in materials with higher yield strength such as titanium will be more difficult to detect than cracks in aluminum. This is illustrated in Table 5.

In view of uncertainty in detection, it is useful to define a confidence level at which flaws or cracks can be found by non-destructive methods. A series of experiments can thus be performed for a given material and flaw geometry to obtain the results as displayed in Figure 16. A confidence level of 80% for detecting a flaw of length 2a = 0.25 cm in aluminum [7].

5.3 Fatigue And Useful Life Of Cracked Hollow Cylinder

Consider a thick-walled cylinder with inner radius b = 17.78 cm and outer radius c = 20.32 cm in Figure 17 (a). It is subjected to an internal pressure that fluctuates in time as shown in Figure 17(b). The maximum internal pressure p_i is 69 MPa while the minimum is zero. The cylinder is made of 300 M steel with μ = 82800 (MPa)

Table 5 - Critical Flaw Size For Aluminum And Titanium Alloys

(1) Aluminum Alloy 7075

Yield Strength: σ_{ys} = 50 to 80 ksi

Toughness: k_{1c} = 25 to 39 ksi$\sqrt{in}$

Critical Crack Size: $2a_c \cong 10^{-1}$ in

(2) Titanium Alloy 6A-6V-2Sn

Yield Strength: σ_{ys} = 150 to 180 ksi

Toughness: k_{1c} = 30 to 50 ksi$\sqrt{in}$

Critical Crack Size: $2a_c \cong 10^{-2}$ in

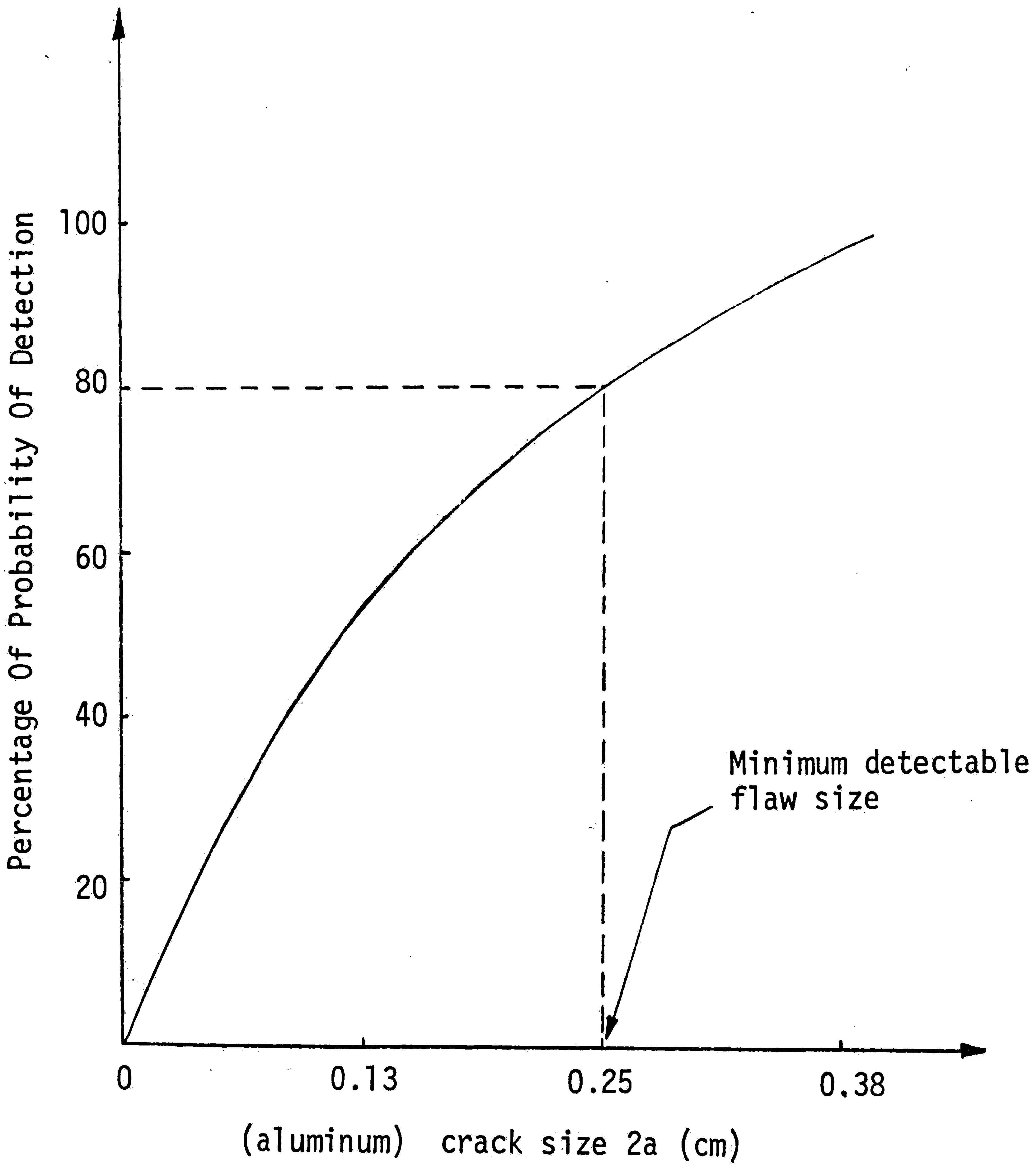
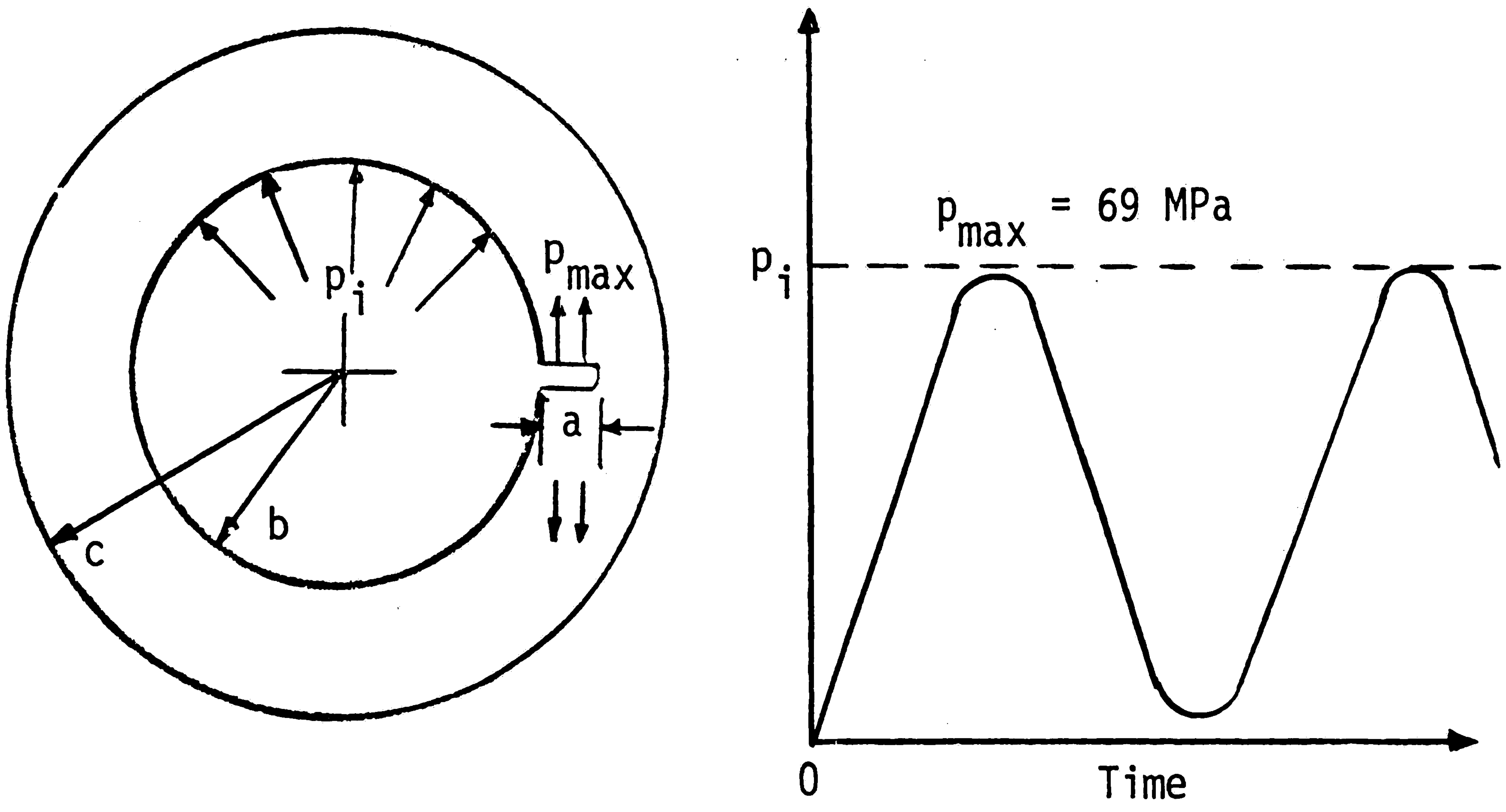


Figure 16. Probability Of Detection As A Function Of Crack Size At A Given Confidence Level.



(a) Pressurized Cylinder (b) Cyclic Pressure

Figure 17. Fatigue Of Pressurized Hollow Cylinder With Edge Crack

and $\nu = 0.25$. Since the stress intensity factor k_1 can be approximated as

$$k_{1c} = 1.12\sigma_{max}\sqrt{\pi a_c} \tag{18}$$

It can be found from equations (4), (18) that

$$S_c = \frac{1-2\nu}{4\mu}k_{1c}^2 = 2.45\text{x}10^{-4}\text{kN/m} \tag{19}$$

in which σ_{max} is obtainable from the strength of material as

$$\sigma_{max} = p\left(\frac{c^2+b^2}{c^2-b^2}\right) = 69\left(\frac{(0.2032)^2+(0.1778)^2}{(0.2032)^2-(0.1778)^2}\right) = 519.8 \text{ MPa} \tag{20}$$

The critical crack length is thus found.

$$a_c = \frac{1}{\pi}\left(\frac{4\mu}{1-2\nu\cdot 1.12\cdot\sigma_{max}}\right)^2 = \frac{1}{\pi}\left(\frac{4\text{x}82800}{1-2\cdot 0.25\cdot 1.12\cdot 519.8}\right)^2$$

$$= 8.2\text{x}10^{-3}(\text{m}) \tag{21}$$

The crack growth relation in equation (21) must be modified with an exponent m on ΔS because damage accumulation is not accounted for by using linear elasticity in computing ΔS, i.e.,

$$\frac{da}{dN} = B(\Delta S)^m \tag{22}$$

For 300 M steel, it can be found from [4] that

$$B = 3\text{x}10^{-9}(\text{m/cycle})(\text{MPa}\sqrt{\text{m}})^{-3} \quad ; \quad \text{and } m = 2 \tag{23}$$

This leads to

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and $\nu = 0.25$. Since the stress intensity factor k_1 can be approximated as

$$k_{1c} = 1.12\sigma_{max}\sqrt{\pi a_c} \tag{18}$$

It can be found from equations (4), (18) that

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The critical crack length is thus found.

$$a_c = \frac{1}{\pi}(\frac{4\mu}{1-2\nu \cdot 1.12 \cdot \sigma_{max}})^2 = \frac{1}{\pi}(\frac{4\text{x}82800}{1-2 \cdot 0.25 \cdot 1.12 \cdot 519.8})^2$$

$$= 8.2\text{x}10^{-3}(\text{m}) \tag{21}$$

The crack growth relation in equation (21) must be modified with an exponent m on ΔS because damage accumulation is not accounted for by using linear elasticity in computing ΔS, i.e.,

$$\frac{da}{dN} = B(\Delta S)^m \tag{22}$$

For 300 M steel, it can be found from [4] that

$$B = 3\text{x}10^{-9}(\text{m/cycle})(\text{MPa}\sqrt{\text{m}})^{-3} \quad ; \quad \text{and } m = 2 \tag{23}$$

This leads to

$$\frac{da}{dN} = C(\Delta S)^n = C(\frac{1-2\gamma}{4\mu}) \cdot (1.12 \cdot 519.8 \cdot \sqrt{\pi a})^4$$

$$= 3x10^{-9} \cdot 1.6x10^{-6} \cdot 1.10x10^{12} \cdot a^2 \qquad (24)$$

$$= 5.27x10^{-3}\ a^2$$

Integration yields

$$\int_{a_i}^{a_f} \frac{da}{5.27x10^{-3}a^2} = \int_{N_i}^{N_f} dN \qquad (25)$$

and

$$N_f = \frac{1}{5.27x10^{-3}} (\frac{1}{a_i} - \frac{1}{a_f}) \qquad (26)$$

For $a_i = 0.00127m$ and $a_f = a_c = 8.2x10^{-3}m$ in equation (21), it is found that

$$N_f = 1.26x10^5 \text{ cycles} \qquad (27)$$

If a 85% useful life is assumed, then

$$a_f = 8.2x10^{-3} \cdot 0.85 = 6.97x10^{-3}m \qquad (28)$$

which corresponds to $N_f = 1.22x10^5$ cycles. The interval for NDT inspection may be set between 55000 ~ 70000 cycles, i.e.,

$a_f = 0.0020m$ for $N_f = 55,000$ cycles and

$a_f = 0.0024m$ for $N_f = 70,000$ cycles. The results of a, N and da/dN can be found in Table 6.

Table 6. Crack Growth Rate For 300M Steel With Stress Amplitude 69MPa

$a(m \times 10^{-3})$	$N(\text{cycles} \times 10^{4})$	$\Delta a/\Delta N(\frac{m}{\text{cycles}} \times 10^{-9})$
1.27	0	0
1.36	1	9.00
1.46	2	9.50
1.59	3	10.10
1.73	4	11.50
1.91	5	12.80
2.12	6	14.17
2.39	7	16.00
2.74	8	18.38
3.20	9	21.44
3.85	10	25.80
4.82	11	32.27
6.47	12	43.33
8.20	12.6	55.00

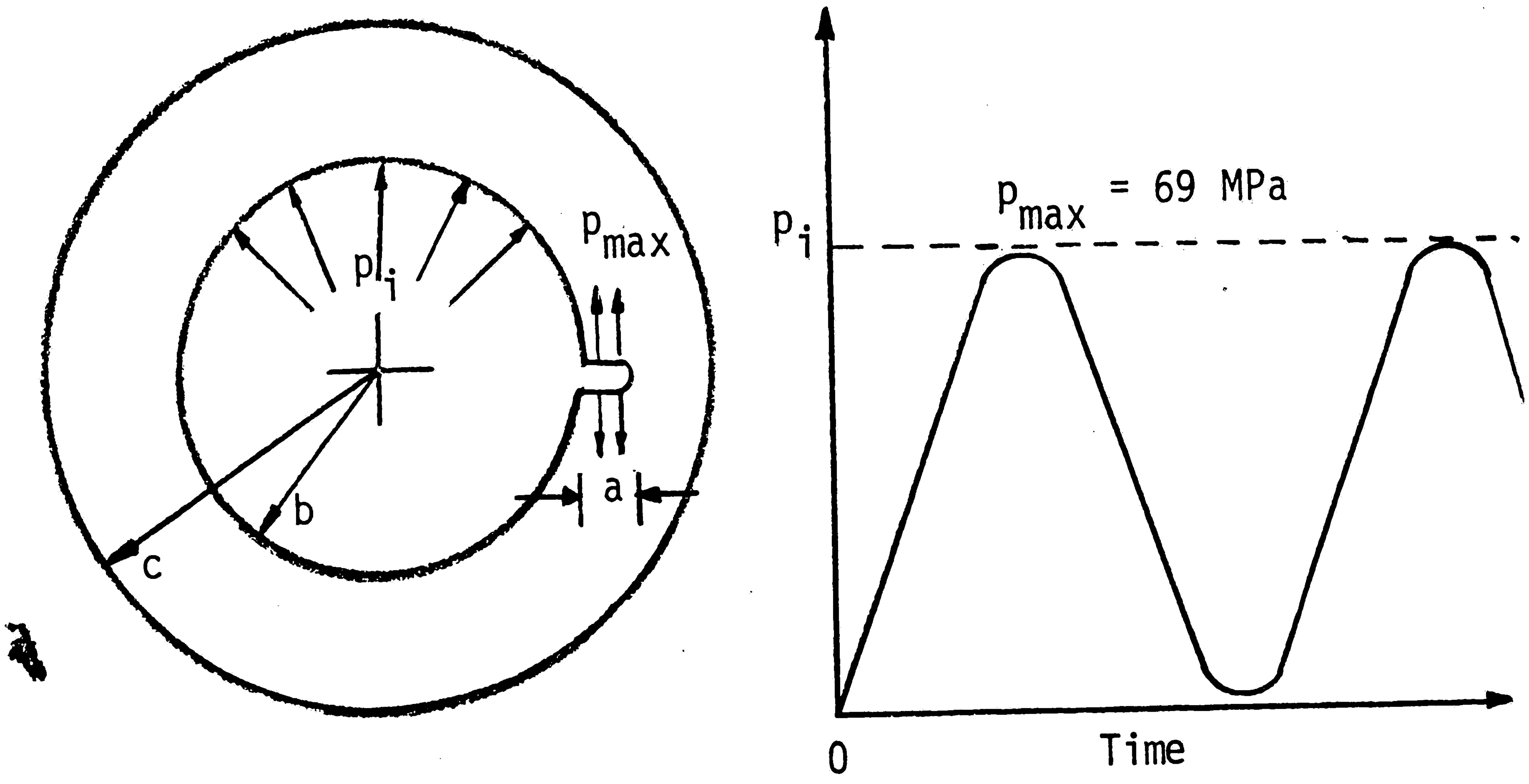
5.4 Non-Destructive Evaluation

Example for NDT Method (flaw criticality evaluation)

Rating for an inspectable crack length

$$a_s = a_c\ (1-I)(1-D) \tag{29}$$

Fatigue Of Pressurized Hollow Cylinder With Edge Crack



(a) Pressurized Cylinder (b) Cyclic Pressure

c = 20.32 cm , b = 17.78 cm , Material.. 300 M steel

maximum internal pressure (P_{max}) = 69 MPa

critical stress intensity factor parameter $k_{1c} = 93.47\ \text{MPa}\sqrt{m}$

$$\sigma_{max} = P\left(\frac{c^2 + b^2}{c^2 - b^2}\right) = 69\left(\frac{(20.32)^2 + (17.78)^2}{(20.32)^2 - (17.78)^2}\right) = 519.8\ \text{MPa}$$

(direction normal to the crack)

$$\because k_{1c} = 1.12\sigma_{max}\sqrt{\lambda a_c}$$

$$\because a_c = \frac{1}{}\left(\frac{k_{1c}}{1.12\sigma_{max}}\right)^2 = \frac{1}{\lambda}\left(\frac{93.47}{1.12x519.8}\right)^2 = \underline{8.2x10^{-3}m}$$

a. Factors Influencing "I" (Material and Frequency)

Factors	Material	Range	Value of Factor I
k_{1c}(μPa)	Aluminum	High (50+)	0.1
		Medium (40-50)	0.2
		Low (30-40)	0.3
	Steel	High (100+)	0.1
		Medium (80-100)	0.2
		Low (50-80)	0.3
	Titanium	High (70+)	0.1
		Medium (50-70)	0.2
		Low (30-50)	0.3
Inspection Frequency		Continuous	0.1
		Frequent	0.2
		Infrequent	0.3
Other Factor		Aggressive Environment (Stress Corrosion)	0.1
		Complex Failure Mode (No Previous Experience)	0.1

b. Factors Influencing "D" (Operational)

Factors	Range	Value of Factor D
Accessibility	Good Moderate Bad	0.0 0.1 0.2
Surface Finish	Good Moderate Bad	0.0 0.1 0.2
Experience	Available None	0.0 0.1
Comparisons with Standards	Available None	0.0 0.1

c. The Value Of Factor I For This Thick-Walled Cylinder Specimen:

k_{1c} (300 M steel) Med.	0.2
Inspection is frequent	0.1
Complex Failure Mode	0.1
Agressive Environment	0.1
+) (Stress Corrosion)	
	I = 0.5

d. The Value Of Factor D For This Thick-Walled Cylinder Specimen:

Area of inspection (not accessible)	0.2
Surface finish (moderate)	0.1
No experience	0.1
+) No standard available for comparison	0.1
	D = 0.5

$$\because a_s = a_c\,(1-I)(1-D)$$

$$= 8.2\times10^{-3}(1-0.5)(1-0.5)$$

$$\underline{= 2.05\times10^{-3}\ (m)}$$

So the ultrasonic method is recommended.

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APPENDIX: FRACTURE ANALYSIS MATERIAL EVALUATION DATABASE COMPUTER PROGRAM

This program utilizes known data to obtain the critical crack length for a cylinder with a crack subjected to cyclic loading. The user's manual should be referred to for more details [16]. The data bank is constructed and based on the strain energy density theory. Use is made of the incremental theory of plasticity combined with finite element method. A critical crack length is determined from the critical strain energy density function together with the number of cycles to fracture. The following factors are considered:

(1) Material type

(2) Loading condition

(3) Specimen geometry

(4) Flaw size and location

The computer program for the FAMED code follows.

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PAGE(S) 60-87

Computer Program for the FAMED code.

```
LIS

      PROGRAM FAMED(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      CHARACTER STRESS1*3,PEC1*1,TAX1*1,TAX2*1,TAX3*1
      INTEGER AMTL
    1 CALL MTL
      WRITE(6,2)
    2 FORMAT(5X,"PLEASE INPUT SELECTED MATERIAL:"/)
      READ*,AMTL
      IF(AMTL.EQ.1)GO TO 3
      IF(AMTL.EQ.2)GO TO 4
      IF(AMTL.EQ.3)GO TO 5
    3 CALL AL
      GO TO 6
    4 CALL ST
      GO TO 6
    5 CALL TI
    6 WRITE(6,7)
    7 FORMAT(5X,"PLEASE INPUT LOADING CONDITION:"/)
      READ(*,100)STRESS1
  100 FORMAT(A3)
      IF(STRESS1.EQ.'I  ')GO TO 8
      IF(STRESS1.EQ.'II ')GO TO 9
      IF(STRESS1.EQ.'III')GO TO 10
```

Computer Program for the FAMED code (Continued)

```
320     8 CALL GOMT1
330       GO TO 81
340     9 CALL GOMT2
350       GO TO 81
360    10 CALL GOMT3
370    81 WRITE(6,11)
380    11 FORMAT(5X,"PLEASE CHOOSE THE SPECIMEN:"/)
390       READ(*,101)PEC1
400   101 FORMAT(A1)
410       IF(PEC1.EQ.'A')GO TO 12
420       IF(PEC1.EQ.'B')GO TO 13
430       IF(PEC1.EQ.'C')GO TO 14
440    12 WRITE(6,432)
450   432 FORMAT("THE INITIAL FLAW SIZE=5.08(CM),AND IS LOCATED AT THE CENTE
460      +R OF THE SPECIMEN,PLS     .TYPE P    "/)
470       READ(*,102)TAX1
480   102 FORMAT(A1)
490       IF(TAX1.EQ.'P')GO TO 104
500   104 WRITE(6,21)
510    21 FORMAT("THE ANSWER FOR YOUR CODE NUMBER IS:"/)
520       IF(AMTL.EQ.1.AND.STRESS1.EQ.'I  '.AND.PEC1.EQ.'A'.AND.TAX1.EQ.'P')
530      +GO TO 22
540       IF(AMTL.EQ.1.AND.STRESS1.EQ.'II '.AND.PEC1.EQ.'A'.AND.TAX1.EQ.'P')

550      +GO TO 23
560       IF(AMTL.EQ.1.AND.STRESS1.EQ.'III'.AND.PEC1.EQ.'A'.AND.TAX1.EQ.'P')
570      +GO TO 24
580       IF(AMTL.EQ.2.AND.STRESS1.EQ.'I  '.AND.PEC1.EQ.'A'.AND.TAX1.EQ.'P')
```

Computer Program for the FAMED code (Continued)

```
590       +GO TO 25
600        IF(AMTL.EQ.2.AND.STRESS1.EQ.'II '.AND.PEC1.EQ.'A'.AND.TAX1.EQ.'P')
610       +GO TO 26
620        IF(AMTL.EQ.2.AND.STRESS1.EQ.'III'.AND.PEC1.EQ.'A'.AND.TAX1.EQ.'P')
630       +GO TO 27
640        IF(AMTL.EQ.3.AND.STRESS1.EQ.'I  '.AND.PEC1.EQ.'A'.AND.TAX1.EQ.'P')
650       +GO TO 28
660        IF(AMTL.EQ.3.AND.STRESS1.EQ.'II '.AND.PEC1.EQ.'A'.AND.TAX1.EQ.'P')
670       +GO TO 29
680        IF(AMTL.EQ.3.AND.STRESS1.EQ.'III'.AND.PEC1.EQ.'A'.AND.TAX1.EQ.'P')
690       +GO TO 30
700     22 WRITE(6,31)
710     31 FORMAT("CRITICAL CRACK LENGTH=10.38(CM),NUMBER OF FAILURE CYCLES=6
720       +125     "/)
730        GO TO 90
740     23 WRITE(6,32)
750     32 FORMAT("CRITICAL CRACK LENGTH=9.22(CM),NUMBER OF FAILURE CYCLES=52
760       +00      "/)
770        GO TO 90

780     24 WRITE(6,33)
790     33 FORMAT("CRITICAL CRACK LENGTH=8.46(CM),NUMBER OF FAILURE CYCLES=36
800       +80      "/)
810        GO TO 90
820     25 WRITE(6,34)
830     34 FORMAT("CRITICAL CRACK LENGTH=9.44(CM),NUMBER OF FAILURE CYCLES=57
840       +05      "/)
850        GO TO 90
860     26 WRITE(6,35)
```

Computer Program for the FAMED code (Continued)

```
 35 FORMAT("CRITICAL CRACK LENGTH=8.02(CM),NUMBER OF FAILURE CYCLES=45
   +35      "/)
    GO TO 90
 27 WRITE(6,36)
 36 FORMAT("CRITICAL CRACK LENGTH=6.82(CM),NUMBER OF FAILURE CYCLES=33
   +25      "/)
    GO TO 90
 28 WRITE(6,37)
 37 FORMAT("CRITICAL CRACK LENGTH=8.75(CM),NUMBER OF FAILURE CYCLES=37
   +50      "/)
    GO TO 90
 29 WRITE(6,38)
 38 FORMAT("CRITICAL CRACK LENGTH=7.19(CM),NUMBER OF FAILURE CYCLES=30
   +50      "/)

    GO TO 90
 30 WRITE(6,39)
 39 FORMAT("CRITICAL CRACK LENGTH=5.38(CM),NUMBER OF FAILURE CYCLES=22
   +30      "/)
    GO TO 90
 13 WRITE(6,433)
433 FORMAT("THE INITIAL FLAW SIZE=7.62(CM),AND IS LOCATED AT THE CENTE
   +R OF THE SPECIMEN,PLS     . TYPE Q  "/)
    READ(*,106)TAX2
106 FORMAT(A1)
    IF(TAX2.EQ.'Q')GO TO 499
499 WRITE(6,40)
 40 FORMAT("THE ANSWER FOR YOUR CODE NUMBER IS:        "/)
    IF(AMTL.EQ.1.AND.STRESS1.EQ.'I  '.AND.PEC1.EQ.'B'.AND.TAX2.EQ.'Q')
```

Computer Program for the FAMED code (Continued)

```
1150      +GO TO 41
1160       IF(AMTL.EQ.1.AND.STRESS1.EQ.'II '.AND.PEC1.EQ.'B'.AND.TAX2.EQ.'Q')
1170      +GO TO 42
1180       IF(AMTL.EQ.1.AND.STRESS1.EQ.'III'.AND.PEC1.EQ.'B'.AND.TAX2.EQ.'Q')
1190      +GO TO 43
1200       IF(AMTL.EQ.2.AND.STRESS1.EQ.'I  '.AND.PEC1.EQ.'B'.AND.TAX2.EQ.'Q')
1210      +GO TO 44
1220       IF(AMTL.EQ.2.AND.STRESS1.EQ.'II '.AND.PEC1.EQ.'B'.AND.TAX2.EQ.'Q')
1230      +GO TO 45
1240       IF(AMTL.EQ.2.AND.STRESS1.EQ.'III'.AND.PEC1.EQ.'B'.AND.TAX2.EQ.'Q')
1250      +GO TO 46
1260       IF(AMTL.EQ.3.AND.STRESS1.EQ.'I  '.AND.PEC1.EQ.'B'.AND.TAX2.EQ.'Q')
1270      +GO TO 47
1280       IF(AMTL.EQ.3.AND.STRESS1.EQ.'II '.AND.PEC1.EQ.'B'.AND.TAX2.EQ.'Q')
1290      +GO TO 48
1300       IF(AMTL.EQ.3.AND.STRESS1.EQ.'III'.AND.PEC1.EQ.'B'.AND.TAX2.EQ.'Q')
1310      +GO TO 49
1320    41 WRITE(6,50)
1330    50 FORMAT("CRITICAL CRACK LENGTH=11.16(CM),NUMBER OF FAILURE CYCLES=2
1340      +930      "/)
1350       GO TO 90
1360    42 WRITE(6,51)
1370    51 FORMAT("CRITICAL CRACK LENGTH=9.91(CM),NUMBER OF FAILURE CYCLES=23
1380      +50       "/)
1390       GO TO 90
1400    43 WRITE(6,52)
1410    52 FORMAT("CRITICAL CRACK LENGTH=8.98(CM),NUMBER OF FAILURE CYCLES=17
```

Computer Program for the FAMED code (Continued)

```
1420      +20     "/)
1430       GO TO 90
1440     44 WRITE(6,53)
1450     53 FORMAT("CRITICAL CRACK LENGTH=10.14(CM),NUMBER OF FAILURE CYCLES=2
1460      +550    "/)

1470       GO TO 90
1480     45 WRITE(6,54)
1490     54 FORMAT("CRITICAL CRACK LENGTH=8.80(CM),NUMBER OF FAILURE CYCLES=21
1500      +10     "/)
1510       GO TO 90
1520     46 WRITE(6,55)
1530     55 FORMAT("CRITICAL CRACK LENGTH=7.43(CM),NUMBER OF FAILURE CYCLES=15
1540      +60     "/)
1550       GO TO 90
1560     47 WRITE(6,56)
1570     56 FORMAT("CRITICAL CRACK LENGTH=9.60(CM),NUMBER OF FAILURE CYCLES=16
1580      +40     "/)
1590       GO TO 90
1600     48 WRITE(6,57)
1610     57 FORMAT("CRITICAL CRACK LENGTH=7.89(CM),NUMBER OF FAILURE CYCLES=13
1620      +50     "/)
1630       GO TO 90
1640     49 WRITE(6,58)
1650     58 FORMAT("CRITICAL CRACK LENGTH=6.24(CM),NUMBER OF FAILURE CYCLES=10
1660      +35     "/)
1670       GO TO 90
1680     14 WRITE(6,434)
1690    434 FORMAT("THE INITIAL FLAW SIZE=10.16(CM),AND IS LOCATED AT THE CENT
```

Computer Program for the FAMED code (Continued)

```
     +ER OF THE SPECIMEN,PL    S. TYPE S   "/)
      READ(*,109)TAX3
  109 FORMAT(A1)
      IF(TAX3.EQ.'S')GO TO 110
  110 WRITE(6,59)
   59 FORMAT("THE ANSWER FOR YOUR CODE NUMBER IS:          "/)
      IF(AMTL.EQ.1.AND.STRESS1.EQ.'I  '.AND.PEC1.EQ.'C'.AND.TAX3.EQ.'S')
     +GO TO 60
      IF(AMTL.EQ.1.AND.STRESS1.EQ.'II '.AND.PEC1.EQ.'C'.AND.TAX3.EQ.'S')
     +GO TO 61
      IF(AMTL.EQ.1.AND.STRESS1.EQ.'III'.AND.PEC1.EQ.'C'.AND.TAX3.EQ.'S')
     +GO TO 62
      IF(AMTL.EQ.2.AND.STRESS1.EQ.'I  '.AND.PEC1.EQ.'C'.AND.TAX3.EQ.'S')
     +GO TO 63
      IF(AMTL.EQ.2.AND.STRESS1.EQ.'II '.AND.PEC1.EQ.'C'.AND.TAX3.EQ.'S')
     +GO TO 64
      IF(AMTL.EQ.2.AND.STRESS1.EQ.'III'.AND.PEC1.EQ.'C'.AND.TAX3.EQ.'S')
     +GO TO 65
      IF(AMTL.EQ.3.AND.STRESS1.EQ.'I  '.AND.PEC1.EQ.'C'.AND.TAX3.EQ.'S')
     +GO TO 66
      IF(AMTL.EQ.3.AND.STRESS1.EQ.'II '.AND.PEC1.EQ.'C'.AND.TAX3.EQ.'S')
     +GO TO 67
      IF(AMTL.EQ.3.AND.STRESS1.EQ.'III'.AND.PEC1.EQ.'C'.AND.TAX3.EQ.'S')
```

Computer Program for the FAMED code (Continued)

```
1930        +GO TO 68
1940      60 WRITE(6,69)
1950      69 FORMAT("CRITICAL CRACK LENGTH=12.00(CM),NUMBER OF FAILURE CYCLES=2
1960        +550    "/)
1970         GO TO 90
1980      61 WRITE(6,70)
1990      70 FORMAT("CRITICAL CRACK LENGTH=10.64(CM),NUMBER OF FAILURE CYCLES=1
2000        +805    "/)
2010      62 WRITE(6,71)
2020      71 FORMAT("CRITICAL CRACK LENGTH=9.62(CM),NUMBER OF FAILURE CYCLES=13
2030        +10     "/)
2040         GO TO 90
2050      63 WRITE(6,72)
2060      72 FORMAT("CRITICAL CRACK LENGTH=10.63(CM),NUMBER OF FAILURE CYCLES=1
2070        +950    "/)
2080         GO TO 90
2090      64 WRITE(6,73)
2100      73 FORMAT("CRITICAL CRACK LENGTH=9.44(CM),NUMBER OF FAILURE CYCLES=15
2110        +75     "/)
2120         GO TO 90
2130      65 WRITE(6,74)
2140      74 FORMAT("CRITICAL CRACK LENGTH=8.09(CM),NUMBER OF FAILURE CYCLES=11
2150        +50     "/)
```

Computer Program for the FAMED code (Continued)

```
      GO TO 90
   66 WRITE(6,75)
   75 FORMAT("CRITICAL CRACK LENGTH=10.31(CM),NUMBER OF FAILURE CYCLES=1
     +360    "/)
      GO TO 90
   67 WRITE(6,76)
   76 FORMAT("CRITICAL CRACK LENGTH=8.60(CM),NUMBER OF FAILURE CYCLES=10
     +50     "/)
      GO TO 90
   68 WRITE(6,77)
   77 FORMAT("CRITICAL CRACK LENGTH=6.95(CM),NUMBER OF FAILURE CYCLES=75
     +0      "/)
      GO TO 90
   90 WRITE(6,78)
   78 FORMAT("IF YOU WANT TO DO IT AGAIN,PLS. TYPE 1     "/)
      WRITE(6,79)
   79 FORMAT("IF YOU WANT TO QUIT,PLS. TYPE 2            "/)
      READ*,BOG
      IF(BOG.EQ.1)GO TO 1
      IF(BOG.EQ.2)GO TO 80
   80 STOP
      END
C
```

Computer Program for the FAMED code (Continued)

```
C
      SUBROUTINE MTL
      WRITE(6,300)
  300 FORMAT(10X,"************************************************"/)
      WRITE(6,301)
  301 FORMAT(10X,"**    INSTITUTE OF FRACTURE & SOLID MECHANICS **"/)
      WRITE(6,302)
  302 FORMAT(10X,"**            LEHIGH UNIVERSITY               **"/)
      WRITE(6,303)
  303 FORMAT(10X,"**         DIRECTOR:DR.G. C. SIH              **"/)
      WRITE(6,304)
  304 FORMAT(10X,"************************************************"/)
      WRITE(6,305)
  305 FORMAT("(1)THE DATA BANK IS CONSTRACTED AND BASE ON THE STRAIN ENE
     +RGY DENSITY THEORY.    "/)
      WRITE(6,500)
  500 FORMAT("(2)USED IS MADE OF THE INCREMENTAL THEORY OF PLATICITY COM
     +BINED WITH FINITE ELE    MENT METHOD.  "/)
      WRITE(6,501)
  501 FORMAT("(3)A CRACK LENGTH IS DETERMINED FROM THE CRITICAL STRAIN D
     +ENSITY FUNCTION AND N    UMBER FAILURE CYCLES.    "/)
      WRITE(6,502)
  502 FORMAT("(4)THE FOLLOWING FACTORS ARE CONSIDERED: "/)
```

Computer Program for the FAMED code (Continued)

```
      WRITE(6,306)
  306 FORMAT(5X,"(1)MATERIAL TYPE   "/)
      WRITE(6,307)
  307 FORMAT(5X,"(2)LOADING CONDITION   "/)
      WRITE(6,308)
  308 FORMAT(5X,"(3)SPECIMEN GEOMETRY   "/)
      WRITE(6,309)
  309 FORMAT(5X,"(4)FLAW SIZE AND LOCATION "/)
      WRITE(6,310)
  310 FORMAT("HOW TO USE FAMED: "/)
      WRITE(6,311)
  311 FORMAT(5X,"PLS. CHOOSE THE MATERIAL TYPE FIRST,THERE HAVE ALUMINIU
     +M,STEEL,TITANIUM THREE KINDS OF MATERIAL."/)
      WRITE(6,312)
  312 FORMAT(7X,"(1)IF YOU CHOOSE ALUMINIUM,PLS. TYPE 1   "/)
      WRITE(6,313)
  313 FORMAT(7X,"(2)IF YOU CHOOSE STEEL,PLS. TYPE 2   "/)
      WRITE(6,314)
  314 FORMAT(7X,"(3)IF YOU CHOOSE TITANIUM,PLS. TYPE 3   "/)
      RETURN
      END
C
C
```

Computer Program for the FAMED code (Continued)

```
2850        SUBROUTINE AL
2860        WRITE(6,315)
2870    315 FORMAT("AL: YIELD STRESS   UL.STRESS   Y.P.STRAIN   U.P.STRAIN "/)
2880        WRITE(6,316)
2890    316 FORMAT("      (MPA)          (MPA)                          "/)
2900        WRITE(6,317)
2910    317 FORMAT("      413.69         1585.81       2E-3         4.08E-2 "/)
2920        WRITE(6,318)
2930    318 FORMAT("(1)PLEASE CHOOSE THE LOADING CONDITION,THERE HAVE THREE KI
2940       +NDS OF LOADING CONDIT   IONS   "/)
2950        WRITE(6,319)
2960    319 FORMAT("     MEAN STRESS(MPA)             DELTA STRESS(MPA)     "/)
2970        WRITE(6,320)
2980    320 FORMAT("    =0.5(SIGMAMAX+SIGMAMIN)    =0.5(SIGMAMAX-SIGMAMIN "/)
2990        WRITE(6,321)
3000    321 FORMAT("        206.9                        124.1          "/)
3010        WRITE(6,322)
3020    322 FORMAT("        258.1                        155.2          "/)
3030        WRITE(6,323)
3040    323 FORMAT("        284.5                        170.7          "/)
3050        WRITE(6,324)
3060    324 FORMAT("(2)IF YOU CHOOSE LOADING 1,PLS. TYPE I        "/)
3070        WRITE(6,325)
```

Computer Program for the FAMED code (Continued)

```
  325 FORMAT("(3)IF YOU CHOOSE LOADING 2,PLS. TYPE II        "/)
      WRITE(6,326)
  326 FORMAT("(4)IF YOU CHOOSE LOADING 3,PLS. TYPE III       "/)
      RETURN
      END
C
C
      SUBROUTINE ST
      WRITE(6,327)
  327 FORMAT("ST: YIELD STRESS   UL.STRESS   Y.P.STRAIN   U.P.STRAIN"/)
      WRITE(6,328)
  328 FORMAT("      (MPA)            (MPA)           "/)
      WRITE(6,329)
  329 FORMAT("      517.11           1378.97     2.5E-3       1.34E-2"/)
      WRITE(6,330)
  330 FORMAT("(1)PLEASE CHOOSE THE LOADING CONDITION,THERE HAVE THREE KI
     +NDS OF LOADING CONDI    TION                    "/)
      WRITE(6,331)
  331 FORMAT("     MEAN STRESS(MPA)               DELTA STRESS(MPA)     "/)
      WRITE(6,332)
  332 FORMAT("     =0.5(SIGMAMAX+SIGMAMIN)    =0.5(SIGMAMAX-SIGMAMIN)"/)
      WRITE(6,333)
  333 FORMAT("           206.9                        124.1          "/)
```

Computer Program for the FAMED code (Continued)

```
      WRITE(6,334)
  334 FORMAT("          258.1                         155.2          "/)
      WRITE(6,335)
  335 FORMAT("          284.5                         170.7          "/)
      WRITE(6,336)
  336 FORMAT("(2)IF YOU CHOOSE LOADING 1,PLS. TYPE I         "/)
      WRITE (6,337)
  337 FORMAT("(3)IF YOU CHOOSE LOADING 2,PLS. TYPE II        "/)
      WRITE (6,338)
  338 FORMAT("(4)IF YOU CHOOSE LOADING 3,PLS. TYPE III       "/)
      RETURN
      END
C
C
      SUBROUTINE TI
      WRITE(6,339)
  339 FORMAT("TI: YIELD STRESS   UL.STRESS   Y.P.STRESS   U.P.STRESS"/)
      WRITE(6,340)
  340 FORMAT("       (MPA)          (MPA)           "/)
      WRITE(6,341)
  341 FORMAT("       620.53         1172.12      3E-3        7.04E-3 "/)
      WRITE(6,342)
  342 FORMAT("(1)PLEASE CHOOSE THE LOADING CONDITION,THERE HAVE THREE KI
```

Computer Program for the FAMED code (Continued)

```
     +NDS OF LOADING CONDI     TION           "/)
      WRITE(6,343)
  343 FORMAT("     MEAN STRESS(MPA)            DELTA STRESS(MPA)      "/)
      WRITE(6,344)
  344 FORMAT("     =0.5(SIGMAMAX+SIGMAMIN)     =0.5(SIGMAMAX-SIGMAMIN)"/)
      WRITE(6,345)
  345 FORMAT("          206.9                       124.1          "/)
      WRITE(6,346)
  346 FORMAT("          258.1                       155.2          "/)
      WRITE(6,347)
  347 FORMAT("          284.5                       170.7         "/)
      WRITE(6,348)
  348 FORMAT("(2)IF  YOU CHOOSE LOADING 1,PLS.  TYPE I       "/)
      WRITE(6,349)
  349 FORMAT("(3)IF  YOU CHOOSE LOADING 2,PLS.  TYPE II      "/)
      WRITE(6,350)
  350 FORMAT("(4)IF  YOU CHOOSE LOADING 3,PLS.  TYPE III     "/)
      RETURN
      END
C
C
      SUBROUTINE GOMT1
      WRITE(6,351)
```

Computer Program for the FAMED code (Continued)

```
  351 FORMAT("L1: MEAN STRESS(MPA)           DELTA STRESS(MPA)"/)
      WRITE(6,352)
  352 FORMAT("       206.9                          124.1     "/)
      WRITE(6,353)
  353 FORMAT("PLEASE CHOOSE THE SPECIMEN,THERE HAVE THREE KINDS OF SPECI
     +MEN:         "/)
      WRITE(6,354)
  354 FORMAT(5X,"(A)CYLINDER(CM):             "/)
      WRITE(6,355)
  355 FORMAT("        L=50.8, R=12.7, V/A=5.08              "/)
      WRITE(6,356)
  356 FORMAT("        L=76.2, R=19.3, V/A=7.62              "/)
      WRITE(6,357)
  357 FORMAT("        L=101.6,R=25.4, V/A=10.16             "/)
      WRITE(6,358)
  358 FORMAT(5X,"(B)HOLLOW CYLINDER(CM):                     "/)
      WRITE(6,359)
  359 FORMAT("        L=36.8, R(O)=9.2, R(I)=4.6, V/A=5.08  "/)
      WRITE(6,360)
  360 FORMAT("        L=55.2, R(O)=13.8,R(I)=6.9, V/A=7.62  "/)
      WRITE(6,361)
  361 FORMAT("        L=73.6, R(O)=18.4,R(I)=9.2, V/A=10.16 "/)
      WRITE(6,362)
```

Computer Program for the FAMED code (Continued)

```
4000    362 FORMAT(5X,"(C)PLATE(CM):                                        "/)
4010        WRITE(6,363)
4020    363 FORMAT("          L=233.68, W=116.84, D=11.68, V/A=5.08   "/)
4030        WRITE(6,364)
4040    364 FORMAT("          L=350.52, W=175.1,  D=17.51, V/A=7.62   "/)
4050        WRITE(6,365)
4060    365 FORMAT("          L=467.32, W=233.66, D=23.34, V/A=10.16 "/)
4070        WRITE(6,366)
4080    366 FORMAT("(1)IF YOU CHOOSE CYLINDER V/A=5.08,PLS. TYPE A "/)
4090        WRITE(6,367)
4100    367 FORMAT("(2)IF YOU CHOOSE CYLINDER V/A=7.62,PLS. TYPE B "/)
4110        WRITE(6,368)
4120    368 FORMAT("(3)IF YOU CHOOSE CYLINDER V/A=10.16,PLS. TYPE C "/)
4130        WRITE(6,369)
4140    369 FORMAT("(4)IF YOU CHOOSE HOLLOW CYLINDER V/A=5.08,PLS. TYPE D"/)
4150        WRITE(6,370)
4160    370 FORMAT("(5)IF YOU CHOOSE HOLLOW CYLINDER V/A=7.62,PLS. TYPE E"/)
4170        WRITE(6,371)
4180    371 FORMAT("(6)IF YOU CHOOSE HOLLOW CYLINDER V/A=10.16,PLS. TYPE F"/)
4190        WRITE(6,372)
4200    372 FORMAT("(7)IF YOU CHOOSE PLATE V/A=5.08,PLS. TYPE G   "/)
4210        WRITE(6,373)
4220    373 FORMAT("(8)IF YOU CHOOSE PLATE V/A=7.62,PLS. TYPE H   "/)
```

Computer Program for the FAMED code (Continued)

```
      WRITE(6,374)
  374 FORMAT("(9)IF YOU CHOOSE PLATE V/A=10.16,PLS. TYPE I "/)
      RETURN
      END
C
C
      SUBROUTINE GOMT2
      WRITE(6,384)
  384 FORMAT("L2: MEAN STRESS(MPA)             DELTA STRESS(MPA)   "/)
      WRITE(6,385)
  385 FORMAT("       258.1                         155.2          "/)
      WRITE(6,386)
  386 FORMAT("PLEASE CHOOSE THE SPECIMEN,THREE HAVE THREE KINDS OF SPECI
     +MEN:       "/)
      WRITE(6,387)
  387 FORMAT(5X,"(A)CYLINDER(CM):                                  "/)
      WRITE(6,388)
  388 FORMAT("         L=50.8, R=12.7, V/A=5.08                    "/)
      WRITE(6,389)
  389 FORMAT("         L=76.2, R=19.05,V/A=7.62                    "/)
      WRITE(6,390)
  390 FORMAT("         L=101.6,R=25.4, V/A=10.16                   "/)
      WRITE(6,391)
```

Computer Program for the FAMED code (Continued)

```
4460    391 FORMAT(5X,"(B)HOLLOW CYLINDER(CM):                        "/)
4470        WRITE(6,392)
4480    392 FORMAT("         L=36.8, R(O)=9.2, R(I)=4.6, V/A=5.08 "/)
 490        WRITE(6,393)
        393 FORMAT("         L=55.2, R(O)=13.8, R(I)=6.9, V/A=7.62        "/)
4510        WRITE(6,394)
4520    394 FORMAT("         L=73.6, R(O)=18.4, R(I)=9.2, V/A=10.16       "/)
4530        WRITE(6,395)
4540    395 FORMAT(5X,"(C)PLATE(CM):                                   "/)
4550        WRITE(6,396)
4560    396 FORMAT("         L=233.68, W=116.84, D=11.68, V/A=5.08         "/)
4570        WRITE(6,397)
4580    397 FORMAT("         L=350.52, W=175.1,  D=17.51, V/A=7.62         "/)
4590        WRITE(6,398)
4600    398 FORMAT("         L=467.32, W=233.66, D=23.36, V/A=10.16        "/)
4610        WRITE(6,399)
4620    399 FORMAT("(1)IF YOU CHOOSE CYLINDER V/A=5.08,PLS. TYPE A         "/)
4630        WRITE(6,400)
4640    400 FORMAT("(2)IF YOU CHOOSE CYLINDER V/A=7.62,PLS. TYPE B         "/)
4650        WRITE(6,401)
4660    401 FORMAT("(3)IF YOU CHOOSE CYLINDER V/A=10.16,PLS. TYPE C        "/)
4670        WRITE(6,402)
4680    402 FORMAT("(4)IF YOU CHOOSE HOLLOW CYLINDER V/A=5.08,PLS. TYPE D "/)
```

Computer Program for the FAMED code (Continued)

```
      WRITE(6,403)
  403 FORMAT("(5)IF YOU CHOOSE HOLLOW CYLINDER V/A=7.62,PLS. TYPE E "/)
      WRITE(6,404)
  404 FORMAT("(6)IF YOU CHOOSE HOLLOW CYLINDER V/A=10.16,PLS. TYPE F"/)
      WRITE(6,405)
  405 FORMAT("(7)IF YOU CHOOSE PLATE V/A=5.08,PLS. TYPE G           "/)
      WRITE(6,406)
  406 FORMAT("(8)IF YOU CHOOSE PLATE V/A=7.62,PLS. TYPE H           "/)
      WRITE(6,407)
  407 FORMAT("(9)IF YOU CHOOSE PLATE V/A=10.16,PLS. TYPE I          "/)
      RETURN
      END
C
C
      SUBROUTINE GOMT3
      WRITE(6,408)
  408 FORMAT("L3: MEAN STRESS           DELTA STRESS            "/)
      WRITE(6,409)
  409 FORMAT("      284.5                   170.7               "/)
      WRITE(6,410)
  410 FORMAT("PLEASE CHOOSE THE SPECIMEN,THERE HAVE THREE KINDS OF SPECI
     +MEN:     "/)
      WRITE(6,411)
```

Computer Program for the FAMED code (Continued)

```
4920    411 FORMAT(5X,"(A)CYLINDER(CM):                             "/)
4930        WRITE(6,412)
4940    412 FORMAT("          L=50.8, R=12.7, V/A=5.08              "/)
4950        WRITE(6,413)
4960    413 FORMAT("          L=76.2, R=19.05,V/A=7.62              "/)
4970        WRITE(6,414)
4980    414 FORMAT("          L=101.6,R=25.4, V/A=10.16             "/)
4990        WRITE(6,415)
5000    415 FORMAT(5X,"(B)HOLLOW CYLINDER(CM):                      "/)
5010        WRITE(6,416)
5020    416 FORMAT("          L=36.8, R(O)=9.2, R(I)=4.6, V/A=5.08         "/)
5030        WRITE(6,417)
5040    417 FORMAT("          L=55.2, R(O)=13.8,R(I)=6.9, V/A=7.62         "/)
5050        WRITE(6,418)
5060    418 FORMAT("          L=73.6, R(O)=18.4,R(I)=18.4,V/A=10.16        "/)
5070        WRITE(6,419)
5080    419 FORMAT(5X,"(C)PLATE(CM):                                "/)
5090        WRITE(6,420)
5100    420 FORMAT("          L=233.68, W=116.84, D=11.68, V/A=5.08        "/)
5110        WRITE(6,421)
5120    421 FORMAT("          L=350.52, W=175.1,  D=17.51, V/A=7.62        "/)
5130        WRITE(6,422)
5140    422 FORMAT("          L=467.32, W=233.66, D=23.34, V/A=10.16       "/)
```

Computer Program for the FAMED code (Continued)

```
5150          WRITE(6,423)
5160     423  FORMAT("(1)IF YOU CHOOSE CYLINDER V/A=5.08,PLS. TYPE A      "/)
5170          WRITE(6,424)
5180     424  FORMAT("(2)IF YOU CHOOSE CYLINDER V/A=7.62,PLS. TYPE B      "/)
5190          WRITE(6,425)
5200     425  FORMAT("(3)IF YOU CHOOSE CYLINDER V/A=10.16,PLS. TYPE C     "/)
5210          WRITE(6,426)
5220     426  FORMAT("(4)IF YOU CHOOSE HOLLOW CYLINDER V/A=5.08,PLS. TYPE D  "/)
5230          WRITE(6,427)
5240     427  FORMAT("(5)IF YOU CHOOSE HOLLOW CYLINDER V/A=7.62,PLS. TYPE E  "/)
5250          WRITE(6,428)
5260     428  FORMAT("(6)IF YOU CHOOSE HOLLOW CYLINDER V/A=10.16,PLS. TYPE F "/)
5270          WRITE(6,429)
5280     429  FORMAT("(7)IF YOU CHOOSE PLATE V/A=5.08,PLS. TYPE G         "/)
5290          WRITE(6,430)
5300     430  FORMAT("(8)IF YOU CHOOSE PLATE V/A=7.62,PLS. TYPE H         "/)
5310          WRITE(6,431)
5320     431  FORMAT("(9)IF YOU CHOOSE PLATE V/A=10.16,PLS. TYPE I        "/)
5330          RETURN
5340          END
```

EXAMPLE

```
FAMED     23:51    FT5
          **********************************************
          **    INSTITUTE OF FRACTURE & SOLID MECHANICS **
          **             LEHIGH UNIVERSITY              **
          **          DIRECTOR:DR.G. C. SIH             **
          **********************************************
(1)THE DATA BANK IS CONSTRACTED AND BASE ON THE STRAIN ENERGY DENSITY THEORY.
(2)USED IS MADE OF THE INCREMENTAL THEORY OF PLATICITY COMBINED WITH FINITE ELE
   MENT METHOD.
(3)A CRACK LENGTH IS DETERMINED FROM THE CRITICAL STRAIN DENSITY FUNCTION AND N
   UMBER FAILURE CYCLES.
(4)THE FOLLOWING FACTORS ARE CONSIDERED:

     (1)MATERIAL TYPE
     (2)LOADING CONDITION
     (3)SPECIMEN GEOMETRY
     (4)FLAW SIZE AND LOCATION
```

Example (Continued)

```
HOW TO USE FAMED:

     PLS. CHOOSE THE MATERIAL TYPE FIRST,THERE HAVE ALUMINIUM,STEEL,TITANIUM THR
EE KINDS OF MATERIAL.

          (1)IF YOU CHOOSE ALUMINIUM,PLS. TYPE 1

          (2)IF YOU CHOOSE STEEL,PLS. TYPE 2

          (3)IF YOU CHOOSE TITANIUM,PLS. TYPE 3

     PLEASE INPUT SELECTED MATERIAL:

? 2
ST: YIELD STRESS   UL.STRESS   Y.P.STRAIN   U.P.STRAIN

      (MPA)           (MPA)

      517.11          1378.97     2.5E-3        1.34E-2
```

Example (Continued)

```
(1)PLEASE CHOOSE THE LOADING CONDITION,THERE HAVE THREE KINDS OF LOADING CONDI
 TION

     MEAN STRESS(MPA)            DELTA STRESS(MPA)

     =0.5(SIGMAMAX+SIGMAMIN)     =0.5(SIGMAMAX-SIGMAMIN)

           206.9                       124.1

           258.1                       155.2

           284.5                       170.7

(2)IF YOU CHOOSE LOADING 1,PLS. TYPE I

(3)IF YOU CHOOSE LOADING 2,PLS. TYPE II

(4)IF YOU CHOOSE LOADING 3,PLS. TYPE III

     PLEASE INPUT LOADING CONDITION:

? III
L3: MEAN STRESS             DELTA STRESS

      284.5                   170.7
```

Example (Continued)

```
PLEASE CHOOSE THE SPECIMEN,THERE HAVE THREE KINDS OF SPECIMEN:

     (A)SOLID CYLINDER(CM):

        L=50.8, R=12.7, V/A=5.08

        L=76.2, R=19.05,V/A=7.62

        L=101.6,R=25.4, V/A=10.16

     (B)PLATE(CM):

        L=233.68, W=116.84, D=11.68, V/A=5.08

        L=350.52, W=175.1,  D=17.51, V/A=7.62

        L=467.32, W=233.66, D=23.34, V/A=10.16

     (C)HOLLOW CYLINDER(CM):


        L=36.8, R(O)=9.2, R(I)=4.6, V/A=5.08

        L=55.2, R(O)=13.8,R(I)=6.9, V/A=7.62

        L=73.6, R(O)=18.4,R(I)=18.4,V/A=10.16
```

Example (Continued)

```
(1)IF YOU CHOOSE CYLINDER V/A=5.08,PLS. TYPE A

(2)IF YOU CHOOSE CYLINDER V/A=7.62,PLS. TYPE B

(3)IF YOU CHOOSE CYLINDER V/A=10.16,PLS. TYPE C

(4)IF YOU CHOOSE PLATE V/A=5.08,PLS. TYPE D

(5)IF YOU CHOOSE PLATE V/A=7.62,PLS. TYPE E

(6)IF YOU CHOOSE PLATE V/A=10.16,PLS. TYPE F

(7)IF YOU CHOOSE HOLLOW CYLINDER V/A=5.08,PLS. TYPE G

(8)IF YOU CHOOSE HOLLOW CYLINDER V/A=7.62,PLS. TYPE H

(9)IF YOU CHOOSE HOLLOW CYLINDER V/A=10.16,PLS. TYPE I

     PLEASE CHOOSE THE SPECIMEN:

? B
THE INITIAL FLAW SIZE=3.81(CM),AND IS LOCATED AT THE CENTER OF THE SPECIMEN,PLS
    . TYPE Q
```

Example (Continued)

```
? Q
THE ANSWER FOR YOUR CODE NUMBER IS:

CRITICAL CRACK LENGTH=7.43(CM),NUMBER OF FAILURE CYCLES=1560

IF YOU WANT TO DO IT AGAIN,PLS. TYPE 1

IF YOU WANT TO QUIT,PLS. TYPE 2

? 2
    STOP
```

VITA

Kung-Yan Lee was born on December 26, 1956 in I-Lan, Taiwan, Republic of China. His parents are Chung-Ping Lee and Yu-Hsueh Hsieh. He grew up in Taipei and graduated from the Muncipal Cheng-Kung High School in 1976. He will be married to I-Chun Chao in October 1986.

He received the Bachelor of Science degree in the Metallurgical Engineering Department in June, 1980 from Chung Cheng Institute of Technology, Taoyuan, Taiwan. After graduation, he served in the Army for two years and then transferred to the Arsenal in Taipei as an engineer. He was admitted as a graduate student in the Department of Mechanical Engineering and Mechanics at Lehigh University, Bethlehem, Pennsylvania in August, 1984.