Image Cover Sheet

CLASSIFICATION	SYSTEM NUMBER 510323
UNCLASSIFIED	

TITLE

FOUR PC-BASED FRACTURE MECHANICS PACKAGES REVIEWED

System Number:

Patron Number:

Requester:

Notes: Paper #18 contained in Parent Sysnum #510305

DSIS Use only:

Deliver to: DK

#S16323 (18)

Four PC-Based Fracture Mechanics Packages Reviewed

by

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ABSTRACT

The proliferation of powerful personal computing systems has made viable the creation of software programs to determine the fracture mechanics characteristics of engineering materials in various configurations, replacing bulky and time consuming handbooks. This report compares four such programs; NASCRAC, pc-CRACK, Fracture Mechanics and Damage Tolerance Analysis Software (FM&DT) and PC-Failure Assessment Diagram (PC-FAD).

A brief description of each package and a review of their respective features is presented. Each package was rated in terms of their various capabilities and functionality. Comparisons were made based on items such as number and types of geometries, materials libraries, analysis methods, fatigue crack growth capabilities, user interface, user manuals and system requirements. Several representative test problems were attempted with each code to verify accuracy and to highlight limitations.

The code NASCRAC proved superior in many categories with pc-CRACK as a close second. FM&DT suffered from a very poor user interface and PC-FAD was limited in its functionality.

1.0 INTRODUCTION

When studying fracture mechanics an engineer has at his disposal many tools, the premier one being fracture mechanics handbooks. These large texts contain a large quantity of data, such as crack growth rates for various loadings and geometries or material properties, and stress intensity factors for different geometries. This data may be represented in either tabular or plot form. Due to the proliferation of desktop computers, this information has been incorporated into a variety of software packages. Four such computerized packages are evaluated here:

NASCRAC (NASA CRack Analysis Code), by Failure Analysis Associates [1]
PC-FAD (PC-Failure Assessment Diagram), by Babcock & Wilcox [2]
Fracture Mechanics and Damage Tolerance Analysis Software (to be referred to as **F.M. & D.T.**), by FractuREsearch [3]
pc-CRACK, by Structural Integrity Associates [4]

These packages are evaluated and compared with respect to their capabilities and general ease of use. Their capabilities were demonstrated by running several of the respective sample problems included with the software, and by running a common set of test problems on each package.

2.0 SOFTWARE FEATURES

Three of the four packages; NASCRAC, pc-CRACK, and F.M. & D.T. are all similar in scope. These are all multi-purpose packages that allow the user to do a comprehensive fracture mechanics analysis. They fill the role of the handbooks most commonly used in today's engineering office. PC-FAD is a single purpose, failure assessment diagram package. Since PC-FAD lacks the comprehensive abilities of the other packages it cannot be directly compared with the other software.

The comparison consists of separate sections for some features available to the user. For example the number and types of geometries available in each package were looked at. Other points of interest were the types of analysis each package was able to perform, the growth laws it used to perform calculations and the loading forms possible.

2.1 Available Geometries

Flexibility is very important to a software package that is to meet the requirements of a user that may be studying various types of problems. This flexibility is based partially on the number of geometries present and whether they are sufficient for his purpose. If they are not suitable it is important that the software is able to accept input for user definable geometries.

Each package has a set of crack geometries that it uses for analysis. pc-CRACK has two sets of geometric models. There are nineteen geometries available for linear elastic fracture mechanics (LEFM) analysis, and nine geometries for creep and elastic plastic fracture mechanics (EPFM) analysis. NASCRAC has thirty three geometries, while PC-FAD has fifteen and F.M. & D.T. has twelve. Table 1 shows the geometries available in each package. NASCRAC and pc-CRACK also allow the user to input 'a' (crack size) versus 'K' (stress-intensity factor) tables. This allows the user a great amount of flexibility in the problems which may be analyzed. F.M. & D.T. allow the user to include a table of Beta factors (stress intensity correction factors) instead of selecting a geometry. This Beta table may be generated in a separate module (GEOFAC) or may be created by the user. PC-FAD does not allow the user to input his own data.

2.2 Material Libraries

The inclusion of materials data in a software package is an option which, while not essential, is very beneficial, as it frees the user from the time consuming task of looking up the required data from a text. NASCRAC and F.M. &D.T. contain materials data libraries, while pc-CRACK and PC-FAD do not.

NASCRAC's data comes in ten separate data libraries: six aluminum, stainless steel, carbon and alloy steel, titanium, and nickel alloys. Each library contains between one and ten materials records, the constants for the Modified Forman Equation and K_{IC} (critical stress intensity factor). When a material is selected, its data is transferred to the materials' menu in the program where the user may edit it. NASCRAC will only select the data it needs to perform the calculation. The user may input all the data available, then run the model allowing NASCRAC to do the selection of data.

F.M. &D.T.'s data is available through a separate module (MATDAT), but unlike NASCRAC it does not output the raw data. Instead it uses its libraries to output a table (or plot) of ΔK versas $\frac{da}{dN}$ (crack growth rate). This setup is cumbersome since the user must exit MATDAT and then start the module in which the data is to be employed. There are seven libraries: structural steel, austenitic and precipitation hardened stainless steel, general steel, high strength steel, aluminum alloys, titanium alloys, and nickel alloys. Each of these libraries contains individual metals and the instructions needed to create the table (or plot).

Similar in both packages is the ability to use this data in whatever calculation the user might be executing, or the ability to input his own data from another source. The list of materials contained in the NASCRAC and F.M. & D.T. libraries are shown in Table 2.

2.3 Fatigue Crack Growth Analysis

Fatigue crack growth laws are a basic element of fracture mechanics analysis. All the software packages reviewed have options for fatigue crack growth analysis, except PC-FAD. They model the relationship between the rate of crack growth, $\frac{da}{dN}$, and the change in the stress intensity factor, ΔK. Some of the more common crack laws are:

PARIS: $\frac{da}{dN} = C(\Delta K)^m$ where $\Delta K = K_{max} - K_{min}$
C and m are material constants

WALKER: $\frac{da}{dN} = C\left(\frac{\Delta K}{(1-R)^{1-m}}\right)^n$ where $\Delta K = K_{max} - K_{min}$

C, n, and m are material constants
$R = \frac{K_{min}}{K_{max}}$

MODIFIED FORMAN: $$\frac{da}{dN} = C(1-R)^m \Delta K^n \frac{\left(\Delta K - (1 - C_O R)^d \Delta K_O\right)^p}{((1-R)K_c - \Delta K)^q}$$

where $\Delta K = K_{max} - K_{min}$
C, n, m,p,q,d, and C_0 are material constants
$R = \frac{K_{min}}{K_{max}}$
$\Delta K_O = \Delta K$ threshold
K_c is the critical stress intensity factor

All the software packages except PC-FAD have menu selections where the user may choose the fatigue crack growth law to be used. Pc-CRACK has seven selections, F.M. & D.T. has five and NASCRAC has six. F.M. & D.T. has four laws: Paris, Walker, Forman, and Threshold. It also has a tabular input so the user may use custom data for rate of change in stress intensity. pc-CRACK uses the Paris, Walker, Bilinear, Modified Forman, Collipriest, ASME Section XI Bilinear, and Hyperbolic correction fatigue laws. NASCRAC uses the following laws: Paris, Walker, Modified Forman, Collipriest, and Hop-Rau. NASCRAC also permits the option of inputting tabulated data as an alternative to using a predefined crack growth law.

Each package has a menu or module for performing fatigue crack growth analysis and its specific options. An important option in a fatigue crack analysis is the ability to model efficiently the load or stress applied to the test specimen. This means being able to handle random, semi-random, and cyclic (constant) loads. NASCRAC, pc-CRACK, and F.M. & D.T. all have this attribute. Another important feature is the ability to include the effects of peak loads on the growth rate, or retardation. Only NASCRAC and F.M. & D.T. can manage retardation models.

2.4 Stress Corrosion Crack Growth

Stress corrosion crack growth is similar to fatigue crack analysis, but it is the relation between time, 'K', 'a', rate $\frac{da}{dt}$ and the interaction of the material with its environment. Two of the four packages have specific menu or module options related to this.

F.M. & D.T. and pc-CRACK both have specific options affiliated to stress corrosion crack growth. F.M. & D.T. is able to input variable or constant amplitude stresses, while pc-CRACK only needs the maximum applied stress intensity factor, K_{max}. While NASCRAC does not have a specific menu or module for stress corrosion crack growth, it can handle such analysis through its fatigue crack growth option. This involves substituting the rate $\frac{da}{dN}$ and load blocks with the rate $\frac{da}{dt}$ and time.

2.5 Additional Features

Creep analysis is the study of materials at elevated temperatures and under static stress. Creep analysis is only available in pc-CRACK. Only nine predefined geometries are available for this analysis. NASCRAC allows the user to do creep life calculations by using creep crack growth laws.

F.M. & D.T. allows the user to study the probability of crack detection based on such things as crack location and inspection method.

Some other features and outputs are available to the user of these software packages; 'a' versus 'K' plots are available in NASCRAC and pc-CRACK, while only the former offers 'a' versus 'J' output. However, pc-CRACK and NASCRAC both do a number of other J calculations . NASCRAC also offers Crack Opening Area (COA) and life after proof test calculations. All except PC-FAD have options for critical crack size calculations. Only PC-FAD calculates a safety factor for the given data.

2.6 Documentation

With any complicated software, complete documentation is very important. NASCRAC and pc-CRACK both have excellent manuals, full of examples, description and theory. The NASCRAC manual has the bulk of its theory in a separate section, whereas pc-CRACK and F.M. & D.T. have theory combined with the instructions. Unlike the pc-CRACK manual, the F.M. & D.T. documentation is hard to read. The PC-FAD manual provides a good description of the program's operation, but very little theory.

3.0 OPERATION AND EASE OF USE

Each piece of software studied has a menu driven interface, while NASCRAC also gives the user the ability to run it in batch mode, with no user input. All the software support dot matrix printers and plotters, but unfortunately none support laser printers. NASCRAC, pc-CRACK, and PC-FAD give the user the ability to view their plots on the CRT of the computer. All output their plots to a plotter. None of the packages allow the user to output the plots to a printer except through a screen dump, which only applies to the software that displayed the plots on the CRT. pc-CRACK gives the user a file management routine, allowing him to perform various tasks on the stored files. None of the packages allow for mixed units, except where their internal data is in a different unit (pc-CRACK). All but F.M. & D.T. allow the user to save and then restart a session. NASCRAC has an on-line help feature, that the other software lacks. All the software can save files containing their plots and output the data as an ASCII file, allowing the user to plot the data on a separate software package. pc-CRACK has black and white menus, while NASCRAC, F.M. & D.T. and PC-FAD have color menus.

Installation is easy for all; however, NASCRAC uses files backed up on disk, and restores them to the harddrive, which is a cumbersome way to store the software. None of the software except NASCRAC has copy protected software. NASCRAC uses a hardware form of copy protection that protrudes from the parallel port of the computer.

While each program is straightforward and easy to use, some are better than others. NASCRAC, PC-FAD and pc-CRACK are simple in their set ups. Their menu systems allow for the sequencial input of data and finally the output of the answer. Their menu systems lead the user through, with very little reference to the manual. F.M. & D.T. is also menu driven, but the fact that the user has to exit each module and start up another is cumbersome, and impedes the flow of the problem. This is a poor feature, especially for the novice user, as he finds himself constantly referring to the manual to see what each module does. For the user this switching from one program to another becomes very inconvenient.

4.0 SAMPLE PROBLEMS

4.1 Find K For Specific Data

For a flat plate of width W equal to 101.6 mm (4.0 in), containing a centrally positioned internal crack of length 2a equal to 25.4 mm (1.0 in) and under tensile loading, determine the minimum plane strain fracture toughness necessary to ensure fracture will not occur for a design stress of 60000 psi (415 MPa). An exact solution was derived using the following equation [5].

$$Y = \left(\frac{W}{\pi a}\tan\frac{\pi a}{W}\right)^{\frac{1}{2}}$$

The question was also attempted using each software package. pc-CRACK and NASCRAC solved the problem simply and quickly. F.M. & D.T. could not perform the required task with the data given; however, it could calculate Beta (BETA = Y in this example) and this was used to calculate K. PC-FAD could not perform this task at all. The results are as follows:

exact solution	K=85.13
pc-CRACK	K=86.12

NASCRAC	K=86.25
F.M. & D.T.	K=86.24

4.2 Compact Tension Specimen

This example deals with the fatigue crack growth of a compact tension specimen. The specimen was 2.5 in (63.5 mm) wide, 1.25 in (31.75 mm) thick, and had an initial crack size of 0.625 in (15.875 mm). The cyclic load was between zero and 10 ksi (0→68.94 MPa). The specimen was 7075-T6 AL, L-T, 75F. Since PC-FAD doesn't output equivalent data, only NASCRAC, F.M. & D.T. and pc-CRACK were used for this example. The modified Forman equation was used for the NASCRAC and pc-CRACK analysis, with the constants for both coming from the NASCRAC materials library. In F.M. & D.T., since there was no compact specimen geometry in the LICAFF module (used for unretarded fatigue crack growth), a table of crack size and Beta was calculated using the GEOFAC module. Also, since F.M. & D.T. has a material data library, it was used to create a table of growth rates versus the change in stress intensity factors, which was subsequently used in the growth analysis. A summary of the Modified Forman constants is included in Table 3. For the initial crack size, the results for NASCRAC and pc-CRACK are very similar:

pc-CRACK	NASCRAC	F.M. & D.T.
a=0.6254	a=0.6250	R-RATIO=0.1
ΔK=24.92	ΔK=24.57	ΔK=24
da/dN=2.2e-4	da/dN=2.057e-4	da/dN=1.9726e-4

Plots of crack size, a versus growth rate, da/dN may be found in Figure 1 and Figure 2 for pc-CRACK and NASCRAC respectively. These two programs also output K_{max}, K_{min}, and all three can output blocks until failure. Plots of crack length versus K are included in Figures 3 and 4, while plots of K versus da/dN for the three packages may be found in Figures 5 through 7. For interest a plot from PC-FAD for the same data may be found in Figure 8.

4.3 Center Cracked Panel

In this example a plot of stress intensity factor versus crack size is developed so that it can be directly compared with a handbook solution [6]. While F.M. & D.T. was the only package that could output the data in the same fashion as the handbook, with a little manipulation the output from NASCRAC and pc-CRACK could be plotted in the same manner. The handbook represented its stress intensity as a ratio of K_I/K_o and its crack size as the ratio of a/b where a is the half crack length and b is the half panel width. The input width was taken as unity in this problem. K_o is defined as $\sigma\sqrt{\pi a}$.

When the results from the software (Figure 9), and the handbook (Figure 10) are compared, it can be seen that NASCRAC and pc-CRACK are in excellent agreement with the ∞ line, which is the expected result. The results from F.M. & D.T. are less satisfying, however, as they quickly deviate form the handbook`s curve.

4.4 Circumferential Crack in a Cylinder

The purpose of this example is to compare the solutions of the packages using a circumferentially cracked cylinder in tension. Again, a plot of the stress intensity ratio, K_I/K_o is used, but this time its horizontal axis is crack size 'a'. K_o is defined as $\sigma\sqrt{\pi a}$. NASCRAC and pc-CRACK both had resultant curves that were smooth, although they were separated by an almost uniform distance. F.M. & D.T.'s results agreed with the higher results from NASCRAC for half the plot, then agreed with the lower results from pc-CRACK for the remainder of the plot.

5.0 CONCLUSION

Four computerized handbooks containing a variety of features were compared based on capabilities and user friendliness. NASCRAC, pc-CRACK, and F.M. & D.T. are similar in that they are multifunction fracture mechanics analysis tools. PC-FAD is a single purpose analysis tool. It gives the user access to a quick safety reference, based on fracture mechanics. A summary of the various features and characteristics are presented in Table 4. The software package NASCRAC appears to be the most comprehensive, flexible and user friendly.

REFERENCES

1. Failure Analysis Associates, Engineering and Scientific Services, "NASCRAC; NASA CRack Analysis Code Version 2.2", 2225 East Bayshore Road, P.O. Box 51470, Palo Alto, California 94303.

2. Babcock & Wilcox, Alliance Research Center, "PC-Failure Assessment Diagram Revision 4", Alliance, Ohio 44601, April 1990

3. FractuREsearch, "Fracture Mechanics and Damage Tolerance Analysis Software 2nd Edition", 9049 Cupstone Drive, Galena, Ohio, 43021, June 1989

4. Structural Integrity Associates, "pc-CRACK Version 2.0", 3150 Almaden Expressway, Suite 226, San Jose, California 95118.

5. William D. Callister, Jr., Materials Science and Engineering: An Introduction, John Wiley & Sons, Toronto, Ontario, 1991.

6. D.P. Rooke and D.J. Cartwright, Compendium of Stress Intensity Factors, Procurement Executive, Ministry of Defence, Her Majesty`s Stationary Office, London, 1976.

Geometry	F.M. &D.T.	pc-CRACK	PC-FAD	NASCRAC
compact tension	YES, EPFM	YES	YES	YES
disk-shaped compact tension	NO	NO	NO	YES
arc-shaped compact tension	NO	NO	NO	YES
3 point bend	YES, EPFM	NO	NO	YES
center cracked finite plate	YES	YES	YES	YES
cracked infinite plate	NO, USE ABOVE	NO, USE ABOVE	NO, USE ABOVE	YES
single-edge cracked plate	YES	YES	YES	YES
double-edge cracked plate	NO	NO	NO	YES
axial cracked cylinder (ID)	YES	YES	YES	YES
edge cracked solid disk	NO	NO	NO	YES
axial cracked cylinder (OD)	NO	NO	NO	YES
plate through cracked from a hole	YES	INFINITE PLATE	NO	YES
through crack from a hole in a lug	NO	NO	NO	YES
through cracked sphere	NO	NO	NO	YES
axial through cracked cylinder	NO	NO	NO	YES
through cracked cylinder	YES	NO	YES	YES
ID cracked cylinder (circumferential)	YES	YES	YES	YES
OD cracked cylinder (solid) (circumferential)	NO	NO	NO	YES
OD cracked cylinder (circumferential)	NO	NO	NO	YES
edge cracked circular bar	NO	NO	NO	YES
subsurface elliptical cracked plate	NO	YES	NO	YES & USER DEFINED
quarter elliptical cracked plate at a hole	NO	NO		YES
quarter elliptical cracked plate at a lug	NO	NO	NO	YES
corner, quarter elliptical cracked plate	NO	NO, BUT CIRCULAR	NO	YES + USER DEFINED
semi-elliptical surface cracked plate	NO	YES, AND CIRCULAR	NO	YES
semi-elliptical circumferential surface cracked cylinder	NO	NO	NO	YES
semi-elliptical axial surface cracked cylinder	NO	YES	YES	YES
semi-elliptical surface cracked sphere	NO	NO	NO	YES
continuous surface crack in half space	NO	YES	NO	NO
nozzle corner crack	NO	YES	NO	NO
corner crack at hole	YES	NO, USE ABOVE	NO	NO, USE ABOVE
two corner cracks at hole	YES	NO	NO	NO
two through cracks at hole	YES	NO	NO	NO

Table 1. Geometries Available

NASCRAC	F.M. & D.T.
2024-T3 AL, L-T & T-L, 75F	AL 2024 T3 SHEET, LT TL, LAB AIR ,70F
2024-T351 AL, L-T & T-L, 75F	AL 2024 T3 SHEET, LT TL, WET AIR, 70F
2024-T351 AL, L-T & T-L, 300-400F	AL 2024 T3 SHEET, LT TL, SUMP TANK, 70F
2024-T62 AL, L-T & T-L, 75F	AL 2024 T3 SHEET, LT TL, 3.5% NaCl, 70F
2024-T81 AL, L-T & T-L, 75F	AL 2024 T3 SHEET, LT TL, AIR, -65F
2024-T81 AL, L-T & T-L, 350F	AL 2024 T3 SHEET, LT TL, JET FUEL, 70F
2024-T851 AL, L-T, 75F	AL 2024 T351 SHEET, LT TL, LAB AIR, 70F
2024-T851 AL, T-L, 75F	AL 2024 T351 SHEET, LT TL, WET AIR, 70F
2024-T851 AL, T-L, 350F	AL 2024 T351 SHEET, LT TL, SUMP TANK, 70F
2024-T851 AL, L-T & T-L, 75F	AL 2024 T351 SHEET, LT TL, 3.5% NaCl, 70F
2124-T851 AL, L-T, 75F	AL 2024 T351 SHEET, LT TL, AIR, -65F
2124-T851 AL, T-L, 75F	AL 2024 T351 SHEET, LT TL, JET FUEL, 70F
2124-T851 AL, L-T, 350F	AL 2024 T3511 EXTRUSION, LT, LAB AIR, 70F
2124-T851 AL, S-T, 75F	AL 2024 T3511 EXTRUSION, LT, WET AIR, 70F
2124-T851 AL, T-L, -150 TO -200F	AL 2024 T3511 EXTRUSION, LT, SUMP TANK, 70F
2219-T62 AL, L-T &T-L, 75F	AL 2024 T3511 EXTRUSION, LT, 3.5% NaCl, 70F
2219-T62 AL, L-T &T-L, -320F	AL 7049 T73
2219-T62 AL, L-T &T-L, 350F	AL 7049 T7352, HAND
2219-T851 AL, L-T &T-L, 75F	AL 7049 T7352, DIE
2219-T87 AL, L-T, -320F	AL 7050 T651
2219-T87 AL, T-L, -320F	AL 7050 T7351
2219-T87 AL, L-T, 75F	AL 7050 T736
2219-T87 AL, L-T, 300 TO 350F	AL 7050 T76
2219-T87 AL, T-L, 300 TO 350F	AL 7075 T6
2219-T87 AL GTA WELD, AS WELDED, 75F	AL 7075 T7351
2219-T87 AL GTA WELD, AS WELDED, -320F	AL 7075 T7352
2219-T87 AL EB WELD, AS WELDED, 75F	AL 7075 T76
6016-6T AL, L-T & T-L, 75F	AL 7175
6061-T651 AL, L-T & T-L, 75F	AL 7178
6061-T651 AL, L-T, 300F	AL 7475 T6XXX
6061-T651 AL, T-L, 300F	AL 7474 T7XXX
7075-T6 AL, L-T, 75F	AL 357 T6, CHILLED, LT TL, 70F, LAB AIR
7075-T651 AL, L-T, 75F	AL 357 T6, CHILLED, LT TL, 70F, WET AIR
7075-T651 AL, S-T, 75F	AL 357 T6, CHILLED, LT TL, 70F, SUMP TANK
7075-T73 AL, L-T, LHA & HHA, 75F	AL 357 T6, CHILLED, LT TL, 70F, 3.5% NaCl
7075-T7351 AL, L-T,LHA & HHA, 75F	AL 357 T6, UNCHILLED, LT TL, 70F, LAB AIR
7075-T73 AL, T-L, LHA & HHA, 75F, HHA & LAB AIR	AL 357 T6, UNCHILLED, LT TL, 70F, 3.5% NaCl
7075-T7351 AL, T-L, LHA &HHA, 75F, HHA & LAB AIR	AL 357 T6, UNCHILLED, LT TL, 70F, WET AIR
7075-T7651 AL, T-L, 75F	AL 357 T6, UNCHILLED, LT TL, 70F, SUMP TANK
A356-T60 CAST AL, 75F	A-36, ROOM TEMP. (HENCE DENOTED AS RT), AIR
INCO 718 STA, L-T & T-L,75F	A-2128B OR A517F,RT,AIR
INCO 718 STA, L-T, 800F, <1HZ	A-2128B OR A517F, 500F, AIR
INCO 718 STA, L-T, 1000F, <1HZ	A-2128B OR A517F, 650F, AIR
INCO 718 GTA WELD, STA, 75F	A-2128B OR A517F, 800F, AIR
INCO 718 GTA WELD, STA, -320F	A-533B,LT LS TL, RT, AIR
INCO 718 EB WELD, STA, 75F	A-533B, ST, RT, AIR
INCO 718 EB WELD, STA, -320F	A-533B, SL, RT, AIR
AISI 301 SS , 1/2 HARD, 75F	A-533B, 550F, AIR
AISI 304 SS , ANN, 75F	X-65 PIPE STEEL, AIR
AISI 304 SS , SR, 75F	X-65 PIPE STEEL, SALT WATER, 10HZ
AISI 304 SS , ANN, 800F	X-65 PIPE STEEL, SALT WATER 1HZ

Table 2. Materials Included in Libraries

NASCRAC	F.M. & D.T.
AISI 304 SS , WELD SR, 800F	X-65 PIPE STEEL, SALT WATER 0.1HZ
AISI 316 SS , ANN, 75F	X-65 PIPE STEEL, SALT WATER 0.01HZ
AISI 316 SS , ANN, 800F	SS301, ANNEALED, RT
AISI 316 SS , WELD SR, 800F	SS301, 1/2 HARD, RT
4340 STEEL ,180-200 UTS, 75F	SS301, FULL HARD, -400F
D6AC STEEL, 220-240 UTS, HIGH K1C HT, 75F	SS304, ANNEALED, RT
300M STEEL, 280-300 UTS, 75F	SS304, ANNEALED, 1000F
HP9-4-0.20 STEEL, 200 UTS, 1525F 2HRS QQ,X, -65F LHA	SS310, ANNEALED, RT
HP9-4-0.20 STEEL, 200 UTS, 75F	SS310, ANNEALED, -400F
HP9-4-0.20 STEEL, 220-240 UTS, 75F	SS316, ANNEALED, RT
15-5PH STEEL, H1025, 75F	SS316, ANNEALED, 800F
17-4PH STEEL, H1025, 75F	SSPH 13-8Mo, H1000 BAR, LT, DRY AIR, RT
17-4PH STEEL, H900, 75F	SSPH 13-8Mo, H1000 BAR, LT, SUMP TANK, RT
PH13-8Mo STEEL, H1000, 75F	SSPH 13-8Mo, H1000 EXTR., LT, DRY AIR, RT
PH13-8Mo STEEL, H1000, 75F HHA, 1HZ	SSPH 15-5PH, H1025 BAR, LT, LAB AIR, RT
CUSTOM 455 STEEL, H1000, 75F	SSPH 13-8Mo, H1025 BAR, TL, SALT WATER, RT
A286 STEEL STA, 75F	AUSTENITIC STEEL, RT
A286 STEEL STA, 600F	FERRITIC STEEL, RT
A286 STEEL STA, 800F	MARTENSITIC STEEL, RT
A286 STEEL STA, 1000F	STEELS OF 95KSI STRENGTH, RT
TI-6AL-4V RA, L-T & T-L, 75F	STEELS OF 180KSI STRENGTH, RT
TI-6AL-4V RA, L-T & T-L, -100F	STEELS OF 200KSI STRENGTH, RT
TI-6AL-4V BA, L-T & T-L, 75F	LOW ALLOY WELD METAL, UPPER, RT
TI-6AL-4V STA, L-T & T-L, -320F	LOW ALLOY WELD METAL, AVE., RT
TI-6AL-4V STA, L-T & T-L, 75F	LOW ALLOY WELD METAL, LOWER, RT
TI-6AL-4V GTA WELD, SR, 75F	ST4340, TUS=200KSI, LAB AIR, 70F
	STD6AC, LAB AIR, 70F
	STD6AC PLATE, TUS=238KSI, JET FUEL, 70F
	ST 10Ni, TYS=180KSI, LT, LAB AIR, 70F
	ST 300M, TUS=280KSI, LABAIR, 70F
	ST 9-4-02 BAR, TYS=185KSI, LT, LAB AIR, 70F
	ST 9-4-02 BAR, TYS=189KSI, LT, DRY AIR, 70F
	ST 9-4-02 BAR, TYS=189KSI, LT, WET AIR, 70F
	ST 9-4-02 BILLET, TYS=161KSI, LT, LAB AIR, 70F
	ST 9-4-02 BILLET, TYS=178KSI, LT, LAB AIR, 70F
	ST 9-4-02 BILLET, TYS=186KSI, SUMP TANK, 70F
	ST 9-4-03 BAR, TYS=193KSI, LAB AIR, 70F
	ST 9-4-03 FORGING, TYS=198KSI, LAB AIR, 70F
	ST 9-4-03 FORGING, TYS=198KSI, SUMP TANK, 70F
	ST 9-4-02 PLATE, TYS=189KSI, LAB AIR, 70F
	ST AF1410, LAB AIR, 70F
	TI 6AL 4V, MILL ANNEALED, LAB AIR, 70F
	TI 6AL 4V, STA, LAB AIR, 70F
	TI 6AL 4V, RA, LAB AIR, 70F
	TI 6AL 4V, BETA ANNEALED, LAB AIR, 70F
	TI 6AL 6V2SN, MILL ANNEALED, LAB AIR, 70F
	INCONEL 718 BAR, HT F/C 1175F, TYS=160KSI, SL, AIR, RT
	INCONEL 718 BAR, HT F/C 1175F, TYS=160KSI, LT, AIR, RT
	INCONEL 718 BAR, HT F/C 1175F, TYS=160KSI, SL, 400F
	INCONEL 718 BAR, HT F/C 1175F, TYS=160KSI, LT, 400F

Table 2 (cont.). Materials Included in Libraries

C	$2.75*10^{-8}$
m	0
n	2.84
p	0.5
q	0.5
DK_o	2.5
K_c	54.9
C_o	1
d	1
K_{IC}	27

Table 3. Modified Forman Constants (from NASCRAC)

FUNCTION	F.M. & D.T.	pc-CRACK	PC-F.A.D.	NASCRAC
Number of geometries	12	9 or 19	15	33
LEFM	12	19	0	33
Creep	0	9	0	0
EPFM	12	9	0	33
Beta output	yes	no	no	no
Material properties	yes	no	no	yes
Number of materials				
total	85	0	0	76
types of materials	7	0	0	10
Residual strength				
LEFM	yes	no	no	no
EPFM	yes	no	no	no
Fatigue crack growth	yes	yes	no	yes
constant amplitude	yes	yes	no	yes
random amplitude	yes	yes	no	yes
semi -random amplitude	yes	yes	no	yes
with retardation	yes	no	no	yes
without retardation	yes	yes	no	yes
number of growth laws	5	7	0	6
Stress corrosion crack growth	yes	yes	no	no
constant stress	yes	yes	no	no
variable stress	yes	yes	no	no
Other features				
CREEP calculations	no	yes	no	no
Inspection intervals	yes	no	no	no
Instability (J-T analysis)	yes	yes	no	yes
Life after proof test	no	no	no	yes
a vs. K calculations	no	yes	no	yes
a vs. J calculations	no	yes	no	yes
C.O.A. calculations	no	no	no	yes
Critical crack size calculations	yes	yes	no	yes
Failure assesment diagram	no	no	yes	no
Safty Factor	no	no	yes	no

Table 4. Comparison of Software

FUNCTION	F.M. & D.T.	pc-CRACK	PC-F.A.D.	NASCRAC
Operation				
menu driven	yes	yes	yes	yes
printer support	dot	dot	dot	dot
plotter support	HP	HP	HP	HP
plot to printer	no	screen dump	screen dump	screen dump
CRT display of plots	no	yes	yes	yes
ability to save sessions	no	yes	yes	yes
help function	no	no	no	yes
mixed units	no	no	no	no
units available	SI, Imperial	SI, Imperial	SI, Imperial	SI, Imperial
error handling	poor	very good	very good	very good
file management	no	yes	no	no
ASCII data output	yes	yes	yes	yes
save plot files	yes	yes	yes	yes
Manual				
readablity	good	very good	good	very good
theory included	yes	yes	no	yes
example problems	yes	yes	no	yes
samples of output	yes	yes	yes	yes
agreement with program	good	very good	poor	very good

Table 4 (cont.). Comparison of Software

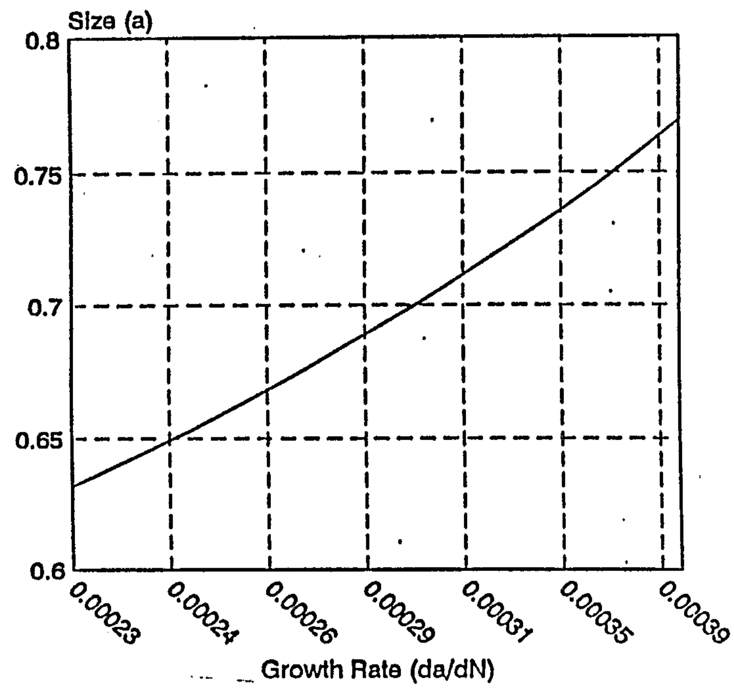

Figure 1. Crack Length vs Growth Rate for pc-CRACK

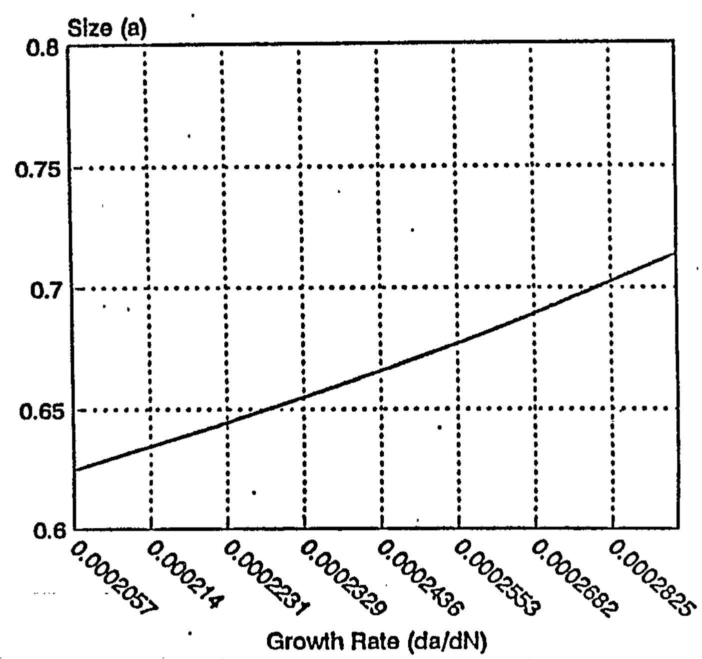

Figure 2. Crack Length vs Growth Rate for NASCRAC

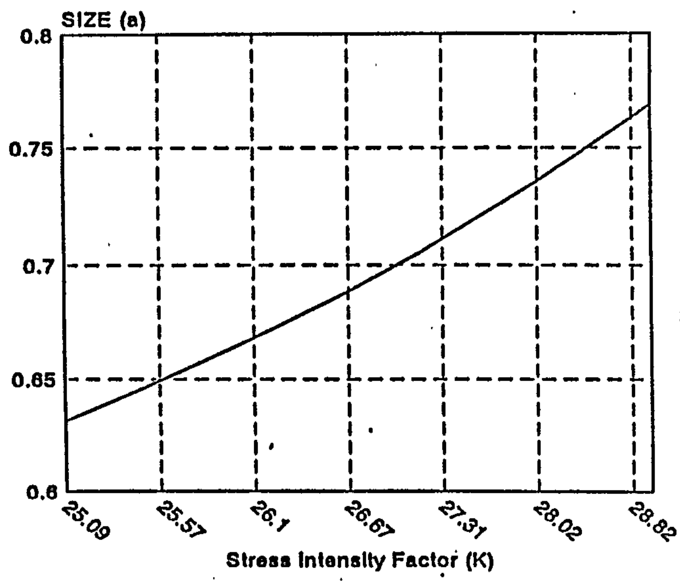

Figure 3. Crack Length vs K for pc-CRACK

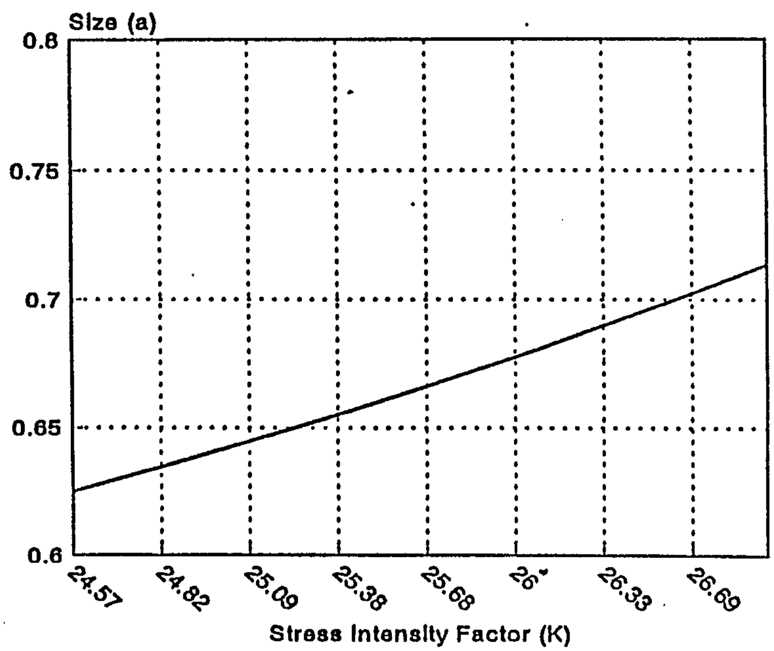

Figure 4. Crack Length vs K for NASCRAC

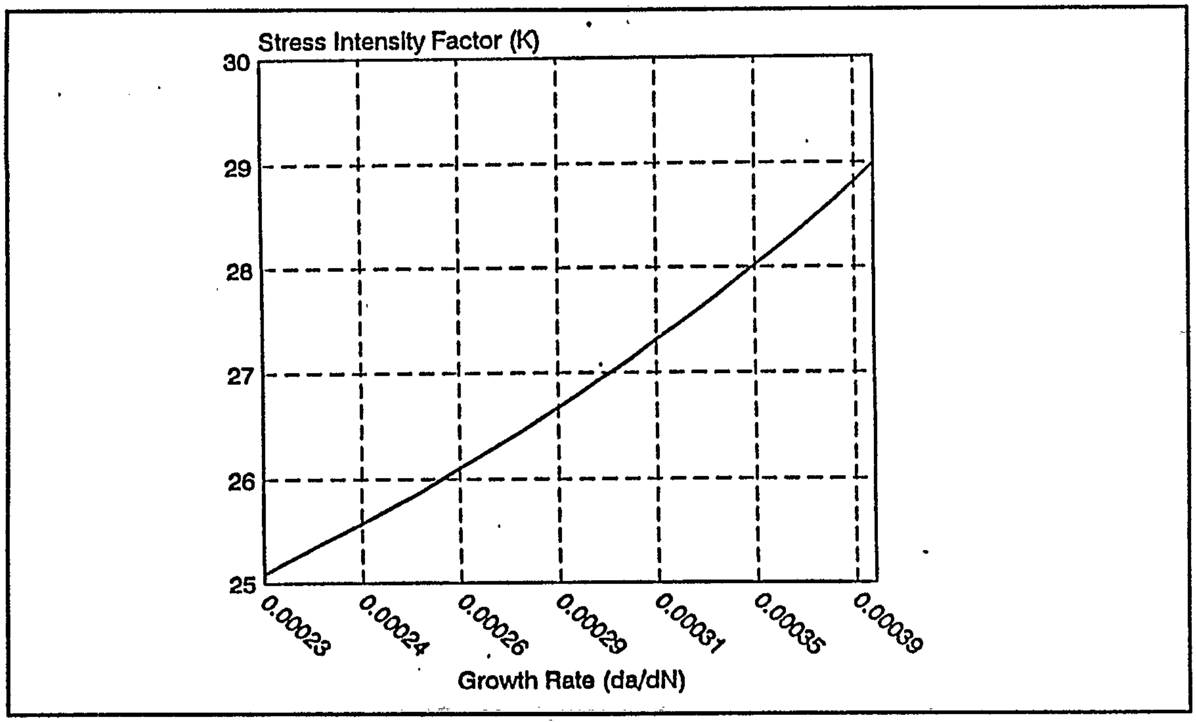

Figure 5. K vs Growth Rate for pc-CRACK

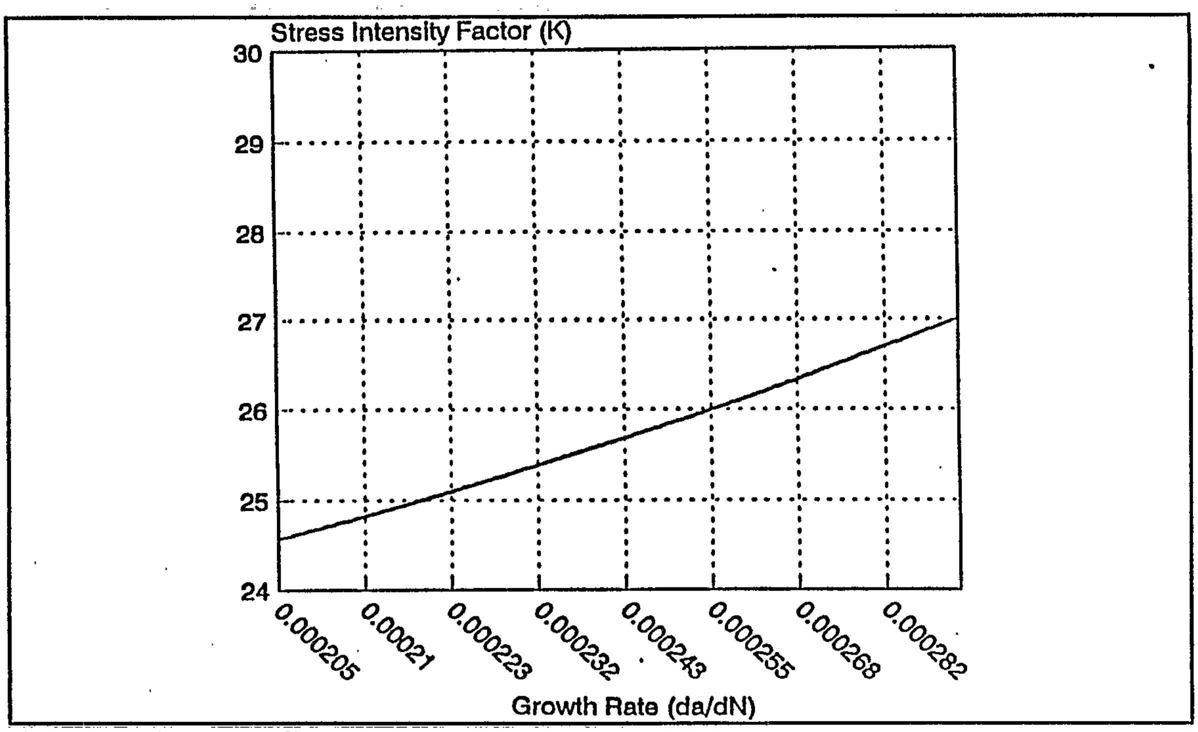

Figure 6. K vs Growth Rate for NASCRAC

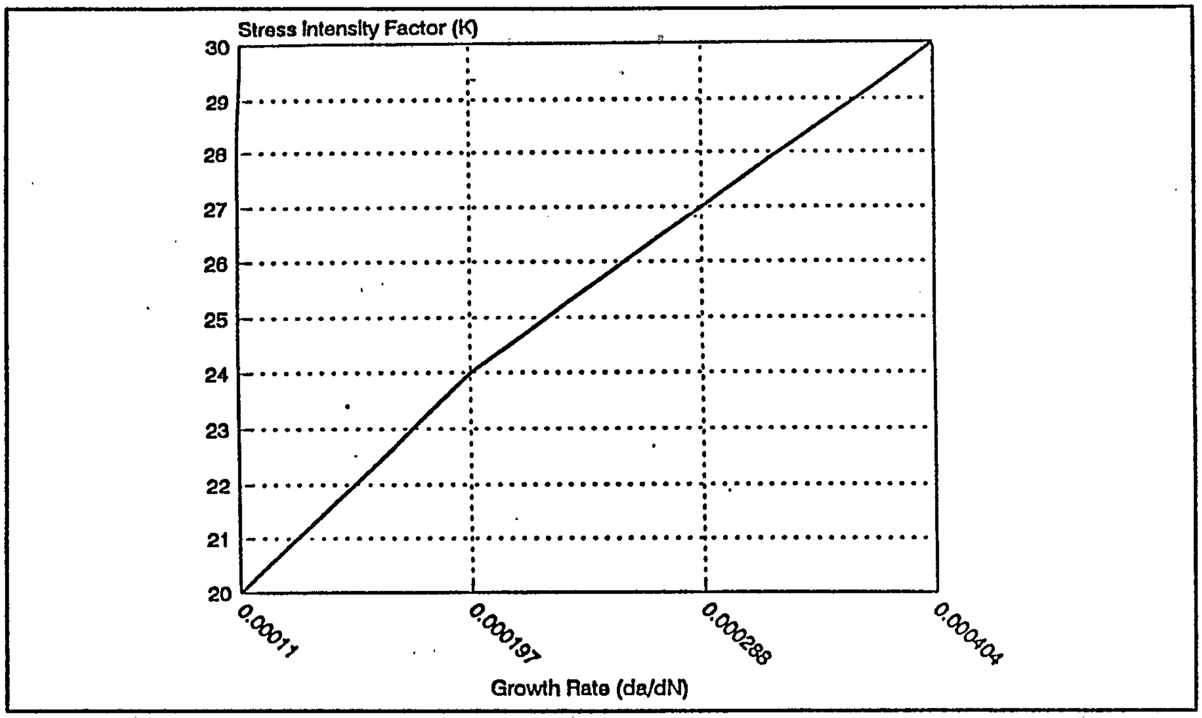

Figure 7. K vs Growth Rate for F.M. & D.T.

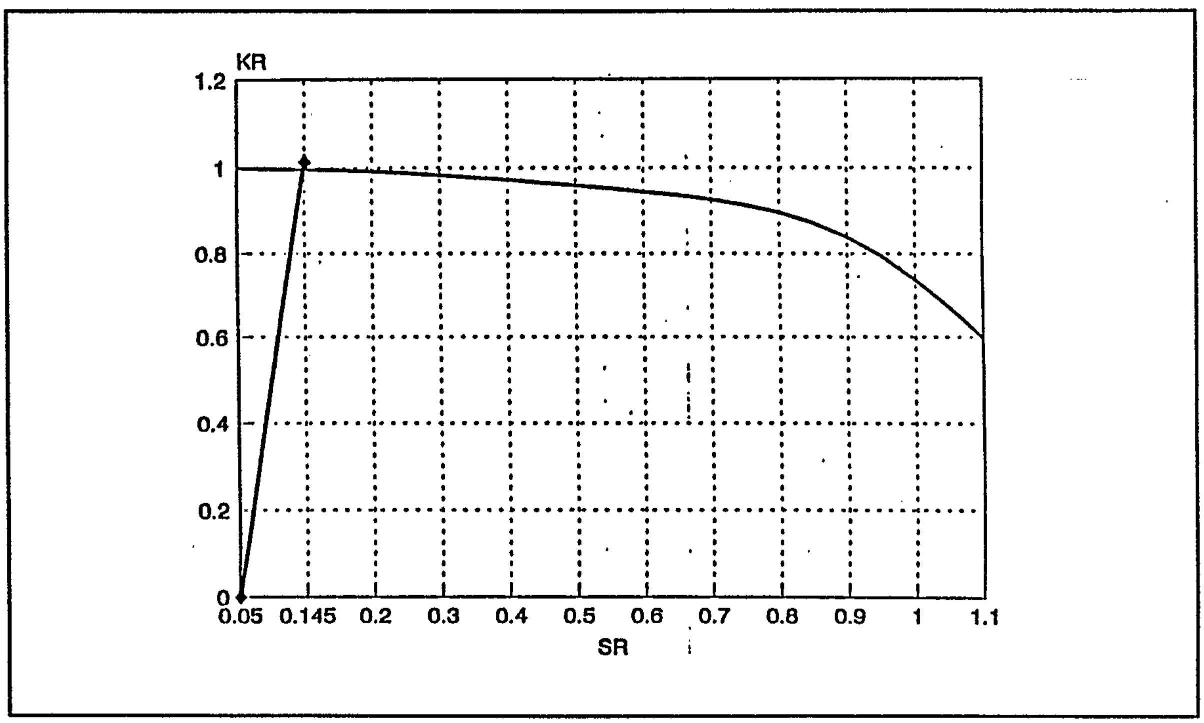

Figure 8. Failure Assessment Diagram from PC-FAD

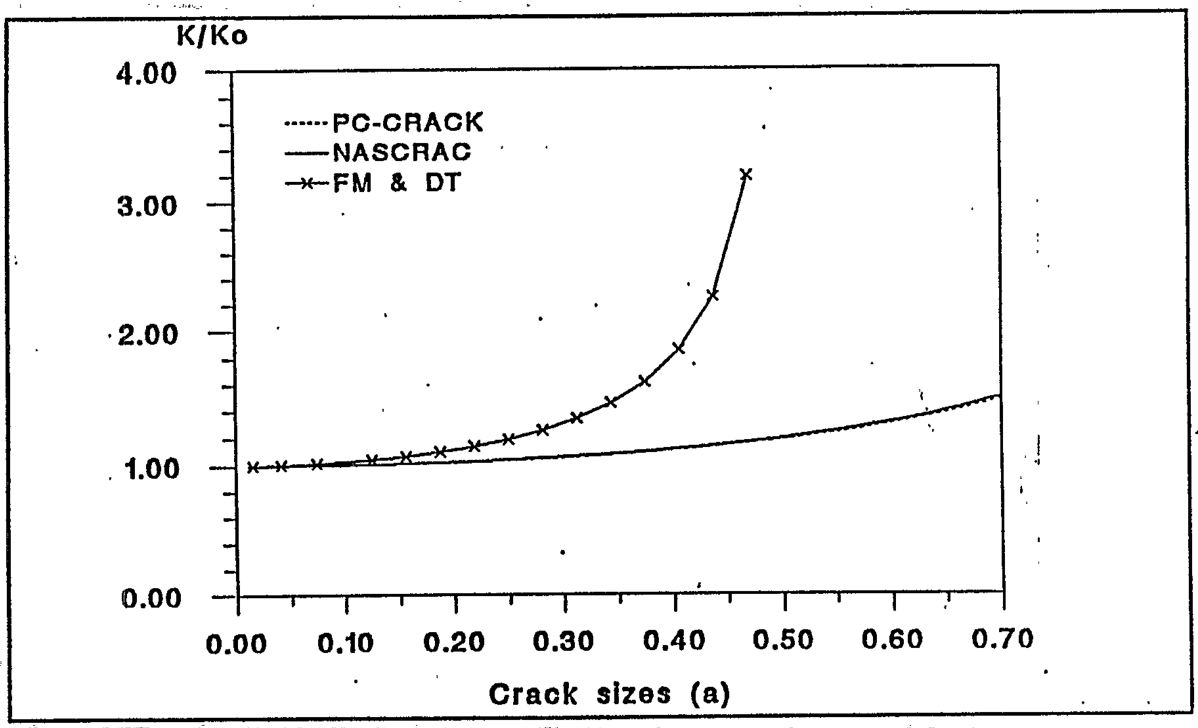

Figure 9. Comparison of K results, flat panel problem

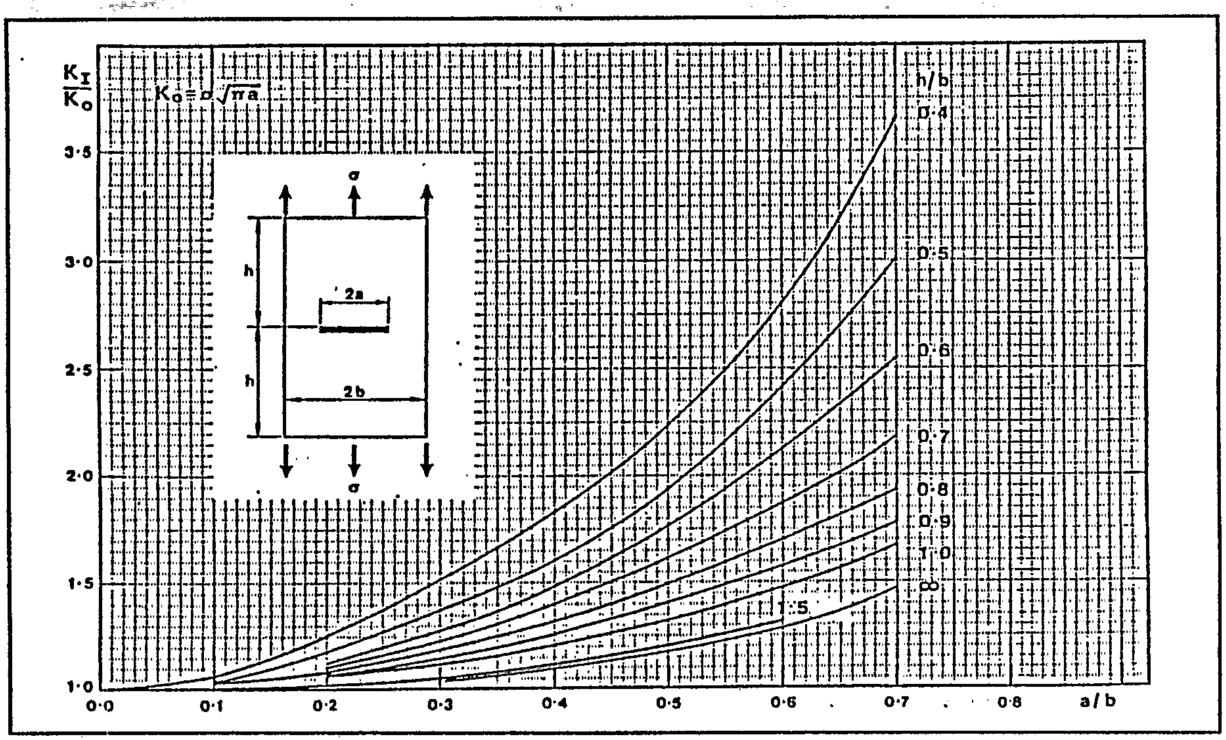

Figure 10. Handbook solution, flat panel problem [8]

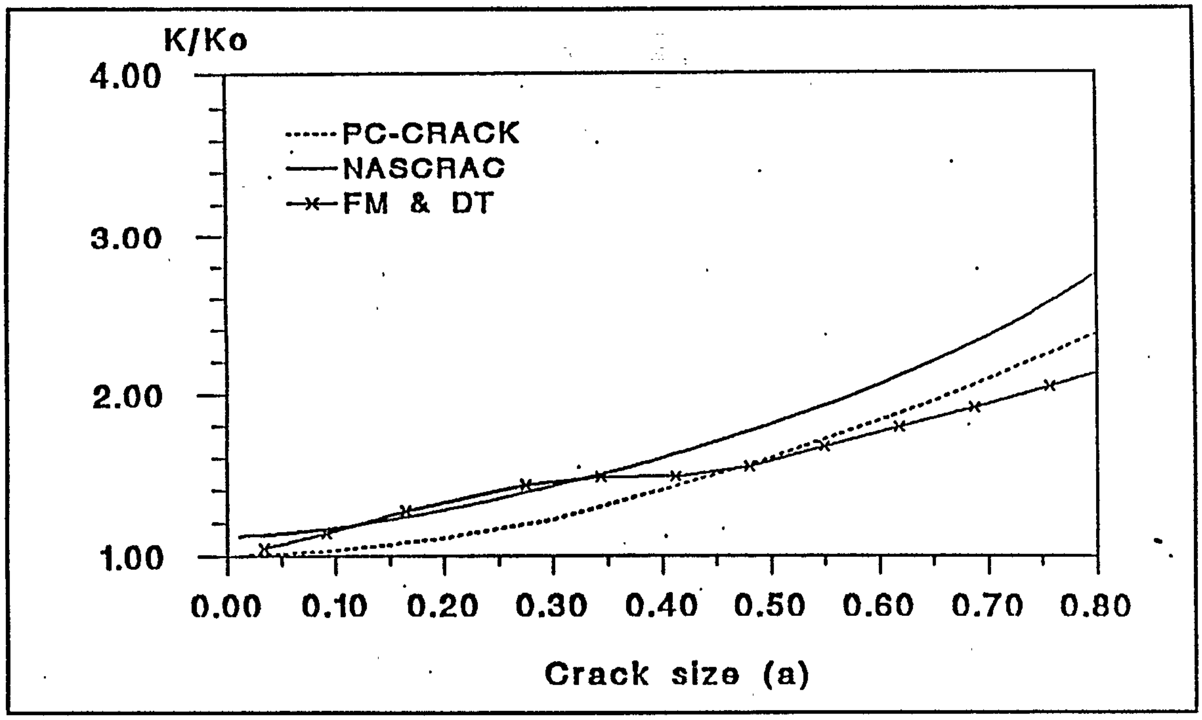

Figure 11. Comparison of K results for cylinder problem

APPENDIX

HARDWARE REQUIREMENTS

Fracture Mechanics & Damage Tolerance Analysis Software

-IBM-PC or compatible
-360K, 5", floppy drive
-DOS
-hard drive (optional)
-dot matrix printer (optional)
-HP plotter (optional)

NASCRAC

-IBM-PC or compatible
-640K
-360K, 5", floppy drive
-DOS 2.11 or better
-hard drive
-monitor (EGA optional)
-dot matrix printer (optional)
-HP plotter (optional)
-Math co-processor (optional)

pc-CRACK

-IBM-PC, XT, AT or compatible
-640K
-2 360K, 5", floppy drive
-1 360K, 5", floppy drive and hard drive (optional)
-DOS 2.0 or better
-CGA card and monitor or better
-dot matrix printer
-HP plotter (optional)

PC-FAD

-IBM-PC, XT, AT or compatible
-256K
-360K, 5", floppy drive
-hard drive (optional)
-DOS 2.10 or better
-CGA card and monitor
-dot matrix printer (optional)
-HP plotter (optional)