MSC-06006

NASA TECHNICAL MEMORANDUM

NASA TM X-58086
February 1972



# COMPUTER ANALYSIS OF TWO-DIMENSIONAL FATIGUE FLAW-GROWTH PROBLEMS

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# ABSTRACT

A description is given of a computer program for analyzing the crack propagation in cyclic loaded structures. By using equations for the stress-intensity factors for surface and embedded flaws, the capability of ascertaining lengthwise crack growth as well as crack growth through the thickness of the structure was determined. Equations used are written in general form so that many other types of crack-growth problems, such as through-the-thickness type cracks, can be analyzed. Provisions have been made in the computer program to analyze crack growth for repeated blocks of variable-amplitude fatigue load spectra. Additional features of the computer program include a variable print interval and a variable integration interval to minimize computer printout and computer run time. A source listing and instructions for using the computer program are included.

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# COMPUTER ANALYSIS OF TWO-DIMENSIONAL FATIGUE FLAW-GROWTH PROBLEMS

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## SUMMARY

A computer program was developed to analyze crack propagation in cyclic loaded structures for both one-dimensional and two-dimensional flaw-growth problems. A sample two-dimensional problem was solved for the growth to crack breakthrough of a surface flaw, and the calculated results were found to compare favorably with experimental results.

This analytic capability was developed in order to help provide the Space Shuttle Program with a reusable vehicle with a long service life. Future work in the area of fatigue crack-growth analysis and testing will consist of deriving a more accurate theoretical solution for the stress-intensity factor of a surface flaw, and studying the flaw-growth rate behavior of different structural materials to be used in the Space Shuttle Program.

## INTRODUCTION

In the Apollo Program, fracture mechanics was used as an analytical and empirical tool to implement fracture control and thus prevent catastrophic failure of main propellant tanks, pressure vessels, and other structural components. The service life of these components was quite short and usually limited to a proof test, a few operational pressure tests, and a single mission cycle. The method of fracture mechanics analysis applied to the Apollo structural components is described in reference 1.

Unlike the Apollo Program, the planned Space Shuttle Program will employ a reusable vehicle with a long service life, and consequently, the fatigue environment and crack-growth problems will be considerably more complex. Because of the longer fatigue life and more complex loading, the pressure vessels, main propellant tanks, and other structural components will require improved crack-growth predictions. Not only will the number of load cycles to fracture be important, but also, in the case of thin-walled tanks, the number of cycles to leak must be considered. Accurate crack-growth predictions will be necessary to define test requirements, nondestructive test flaw detection requirements, and appropriate inspection intervals.

To provide a capability for more general and complex flaw-growth analysis relevant to the Space Shuttle Program, a computer program has been developed to perform analysis for both one-dimensional and two-dimensional flaw-growth problems. The purpose of this report is to describe the theoretical background and the use of this computer program.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

## SYMBOLS

The SI unit conversion factors used with these symbols are listed in appendix A.

| | |
|---|---|
| A | crack depth or crack length, mm (in.) |
| a | semiminor axis of ellipse |
| B | crack half-width or a geometrical dimension, mm (in.) |
| b | semimajor axis of ellipse |
| CA | material constant for crack growth in the A-direction |
| CB | material constant for crack growth in the B-direction |
| DP | stress range in a fatigue cycle, maximum P - minimum P, $MN/m^2$ (ksi) |
| F | correction factor for the effect of the front surface on the growth of a crack through the thickness |
| G | correction factor for the effect of the front surface on the growth of a crack in the width direction |
| K | stress-intensity factor, $MN/(m)^{3/2}$ (ksi$\sqrt{\text{in.}}$) |
| KC, $K_{IC}$ | critical stress-intensity factor for fracture, $MN/(m)^{3/2}$ (ksi $\sqrt{\text{in.}}$) |
| M | correction factor for the effect of the back surface on the growth of a crack through the thickness |
| N | number of fatigue load cycle |
| P | applied stress, $MN/m^2$ (ksi) |
| $P_o$ | stress level at which crack occurs, $MN/m^2$ (ksi) |
| Q | flaw-shape correction factor |

| | |
|---|---|
| R | ratio of minimum applied stress to maximum applied stress in a fatigue cycle |
| S | numerical exponent in the fatigue crack-growth equation |
| T | plate thickness, mm (in.) |
| Y | material yield strength, $MN/m^2$ (ksi) |
| $\Delta K_A$ | stress-intensity factor range used for calculating crack growth in the A-direction, $MN/(m)^{3/2}$ (ksi $\sqrt{in.}$) |
| $\Delta K_B$ | stress-intensity factor range used for calculating crack growth in the B-direction, $MN/(m)^{3/2}$ (ksi $\sqrt{in.}$) |
| $\Phi$ | complete elliptic integral of the second type |
| $\beta, \theta$ | angular coordinates |

## DISCUSSION

Before describing the improved computer analysis developed for fatigue flaw-growth problems, several comments will be made concerning the crack-growth analysis approach used in the Apollo Program. For that analysis, the theory was restricted to elliptically shaped surface and embedded types of flaws and can be expressed by the following functional relationship obtained from reference 1.

$$\frac{d\left(\frac{A}{Q}\right)}{dN} = f\left(\Delta K, \frac{P_o}{P}\right) \tag{1}$$

Two assumptions that are unique and should be noted are made in equation (1). The first assumption is that crack-growth rate can be normalized with respect to the flaw-shape parameter Q. This assumption conflicts with previous crack-growth theories which assume that crack-growth rate at a local point at a crack boundary is governed primarily by the stress-intensity factor at that point (ref. 2). The normalization becomes particularly questionable for large variations in Q such as in the case of a long surface flaw $(A/B < 0.1)$ that grows into the shape of a semicircular flaw before fracture.

The second assumption in equation (1) is that the growth rate must be corrected for the stress-level ratio $P_o/P$. In the ratio, $P_o$ is the stress level at which crack-growth rate data are obtained, and P is the stress level of the crack problem to be analyzed. This ratio was introduced because it was found to be helpful to assume that cycles to fracture $N_c$ was a function only of the ratio $K_{Ii}/K_{IC}$. Curves of $K_{Ii}/K_{IC}$

compared with $N_c$ could be generated from test data, and the crack-growth rate could be determined at a value of $K_{Ii}/K_{IC}$ by measuring the slope of the curve at that value.

The validity of correcting for the ratio $P_o/P$ has never been sufficiently investigated, but the correction is certainly questionable for very small and very large values of $P_o/P$. Applying the correction also conflicts with crack-growth rate theories found to be accurate for through-the-thickness crack-growth problems.

The crack-growth theory used for the computer analysis described in this report was obtained from reference 3. The theory was originally developed for one-dimensional analysis, or growth in one crack dimension only. The theory was investigated in references 4 and 5 and was found to be the most accurate one available for analysis of through-the-thickness cracks in aluminum sheet material. However, the theory has been extended to account for two-dimensional flaw growth, or changed in flaw size in two principal directions for surface and embedded types of flaws. The approach developed is to not normalize flaw-growth rate as is done in equation (1), but to assume that flaw-growth rate in the two principal directions is a function of the stress-intensity factors in these directions.

Other features of the computer program include the ability to analyze numerous problems consecutively, to analyze variable amplitude fatigue loading with different values of the load ratio R and to have block loading that is relevant to studying the effect of repeated Space Shuttle missions.

In the following sections, a complete mathematical formulation of the analysis is described, and instructions for use of the program are provided. Also, comparisons are shown between calculated and experimental results. The program is written in FORTRAN V for the Univac 1108 computer. Conversion factors for the International System of Units (SI) are noted in appendix A. A source listing of the program is given in appendix B, and the input to a sample problem along with the resulting printout is given in appendix C.

## Mathematical Formulation

The basic equations to be solved by the computer program are the differential equations for crack-growth rates in two principal directions (e.g., through the depth of the material and in the plane of the material). The equations to be solved using the crack-growth rate theory from reference 3 have the following forms:

$$\frac{dA}{dN} = \frac{CA\left(\Delta K_A\right)^S}{(1 - R)KC - \Delta K_A} \qquad (2)$$

$$\frac{dB}{dN} = \frac{CB\left(\Delta K_B\right)^S}{(1 - R)KC - \Delta K_B} \qquad (3)$$

The crack-growth rate theory in reference 3 is the most accurate and the best available theory for through-the-thickness cracks. Comparisons with experimental data show that the theory is also valid for two-dimensional flaw-growth analysis.

The greater part of the work in the computer analysis is to determine the values of the parameters $\Delta K_A$ and $\Delta K_B$ and then to solve differential equations (2) and (3) by using the Runge-Kutta numerical integration method. For determining $\Delta K_A$ and $\Delta K_B$, Irwin (ref. 6) has derived the following generally accepted equation for the stress-intensity factor at any location on the crack border of an elliptical crack in an infinite-thickness solid. (See fig. 1(a).)

$$K = P\left(\pi \frac{a}{Q}\right)^{1/2}\left(\sin^2\beta + \frac{a^2}{b^2}\cos^2\beta\right)^{1/4} \tag{4}$$

where

$$Q = \Phi^2 - 0.212\left(\frac{P}{Y}\right)^2 \tag{5}$$

and

$$\Phi = \int_0^{\pi/2}\left[1 - \left(\frac{b^2 - a^2}{b^2}\right)\sin^2\theta\right]^{1/2} d\theta \tag{6}$$

By substituting symbols and appropriate values of $\beta$ as shown in figures 1(b) and 1(c), the following relationships for $\Delta K$ are obtained for the elliptical or semielliptical crack in a finite thickness solid. (See fig. 2.) For a crack propagating in the thickness direction

$$\Delta K_A = F(DP)M\sqrt{\frac{\pi A}{Q}} \quad (\text{if } A \leq B) \tag{7}$$

$$\Delta K_A = F(DP)\left(\frac{B}{A}\right)\sqrt{\frac{\pi A}{Q}} \quad (\text{if } A > B) \tag{8}$$

For a crack propagating in the width direction

$$\Delta K_B = G(DP)\left(\frac{A}{B}\right)\sqrt{\frac{\pi B}{Q}} \text{ (if } A \leq B) \tag{9}$$

$$\Delta K_B = G(DP)\sqrt{\frac{\pi B}{Q}} \text{ (if } A > B) \tag{10}$$

In equations (7) to (10), the usual procedure in fracture mechanics of including correction factors for the finite thickness of a plate (i.e., factors F, G, and M) has been followed. By substituting equations (7) to (10) into equations (2) and (3), all parameters are now a function of the crack geometry and the working stresses and are readily available for the solution of the problem with the exception of F, G, M, and Q.

The parameter F is a correction factor for the effect of the front surface on growth through the thickness. This correction factor has been assumed by Kobayashi and Moss (ref. 7) to be given by the equation

$$F = 1.0 + 0.12\left(1 - \frac{A}{2B}\right)^2 \tag{11}$$

Equation (11) is a proposed interpolation between two extreme cases, Smith's theoretical solution for $A/2B = 0.5$ (ref. 8) and Bowie's theoretical solution for $A/2B = 0$ (ref. 9). Since the extreme values of F vary only between 1.03 and 1.12, the proposed interpolation should give acceptable accuracy.

To make the computer analysis general enough so that problems other than the elliptical flaw can be studied (e.g., one-dimensional through-crack problems), the value of F can be put in either as a constant or as a table. The values for F determined from equation (11) are listed in table I. For other problems, or for different correction factors other than those given by equation (11), the values need only to be substituted for those in table I. If a one-dimensional through-crack problem is to be analyzed, the proper values for the correction factors must be substituted into equation (7), and the option selected in the program to integrate equation (2) only. (Equations (8), (9), and (10) are ignored.)

The parameter G is a correction factor for the effect of the front surface on growth in the width direction. No solution for G has been derived for the semiellipse, but Thresher and Smith (ref. 10) have solved the problem of a partially embedded circular crack by numerical methods. By assuming equal depths and surface lengths for circular and semielliptical surface cracks, the correction factor G can be estimated for the semielliptical crack. This analysis was performed, and some values for G are listed in table II. Because almost all values are approximately 1.12, the procedure shown in figure 1 is to let G be a constant with a value of 1.12.

The parameter M is a correction factor for the effect of the back surface on growth through the thickness. Several approximate solutions exist for M. (See refs. 7 and 11.) For this computer program, the input for the parameter can be either a constant or a table. The values obtained from a recent solution by Shah and Kobayashi are listed in table III and are used in the program. This solution was selected because it is the latest and most accurate numerical solution available. To reduce the complexity of the input requirements, the table for M was programed as data statements into the main program. Details for making changes for this table will be given in the section entitled "Users' Input Instructions."

The final parameter, Q, is a modification of equation (5) to account for cyclic loading at different load ratios. The modified equation for Q is

$$Q = \Phi^2 - 0.212 \left[\frac{DP/(1 - R)}{Y}\right]^2 \tag{12}$$

where $\Phi$ is the elliptic integral given by equation (6). This elliptic integral is a function of the crack geometry and is also put into the program either as a constant value or with the values listed in table IV. The accuracy of equation (12) is difficult to determine, but it should be approximately as accurate as equation (5). Equation (12) assumes small-scale yielding at the crack tip and plane strain conditions. This assumption would be less accurate for relatively high-toughness materials and for calculating $\Delta K_B$ of a surface flaw where plane stress conditions may exist.

It can be seen that the solution of equations (2) and (3) is dependent only upon the availability of the initial crack geometry, the material constants, and the applied cyclic stresses. Growth of the crack for each cycle of load will then be calculated by the computer.

## Description of the Program

Generally, the program integrates the crack propagation rate, equations (2) and (3), to obtain the crack growth in a structure for both the crack depth and the crack half-width at each cycle of load. These load cycles can have variable amplitudes and can be repeated for as many times as the user wishes in order to obtain the complete growth history for the life of the structure.

The program consists of a main program and six subroutines. The main program is called CRACK and has the responsibility of reading in all data, shifting control to the subroutine called CRANE for performing the calculation, and then writing out the results.

Subroutine CRANE does the actual integration of equations (2) and (3) and is dependent on a subroutine called DERIV to supply the derivatives. After the integration has been completed, the control is shifted back to the main program CRACK to write the results.

Subroutine DERIV sets up the derivatives needed for CRANE. The derivatives calculated (depending on the type of flaw) are dA/dN and dB/dN as given by equations (2) and (3). The only derivative that is dependent upon a value of M is equation (2). The parameter M has been inserted as a part of the program and is expressed as either a constant, having a value of 1.0, or in tabular form for a two-dimensional curve of A/T and A/B compared with M as shown in table III. If the tabular values are required for the solution of the problem as in figure 2, then subroutine DISCOT will perform the interpolation for values of M between those given in the table and supply the correct value for the calculation in DERIV. Both equations (2) and (3) are dependent upon a value of Q which is a constant for the case of one-dimensional flaw growth and is a variable for two-dimensional flaw growth. If a two-dimensional flaw-growth problem is to be analyzed, then the user must supply a table of A/B or B/A versus $\Phi^2$ such as the one shown in table IV. Subroutine DISCOT will perform the interpolation for values of $\Phi^2$ for the crack geometry and supply the correct value for the calculation of Q and the subsequent calculations of equations (7) to (10). This same procedure holds for evaluation of the parameter F if it were given as a table.

Subroutine DISCOT is an interpolation routine for determining intermediate points on a curve such as those that would be in the tabular form given above. This subroutine is responsible for determining the proper M, Q, or F values to be used in the calculations of subroutine DERIV. Subroutine DISCOT is dependent upon three other subroutines called UNS, DISSER, and LAGRAN to perform this interpolation.

The general flow of the problem is given as follows. Depending on the type of flaw to be analyzed, the user supplies the original crack geometry, the required material constants, the working stress levels, and the other parameters that are needed for program control. After these cards have been read by the computer, the control is transferred to subroutine CRANE which sets up the necessary format for performing the integration. CRANE then transfers control to subroutine DERIV for calculation of the derivatives.

DERIV is common with the main program and already contains the input crack data and other parameters needed for the solution. Solution of equation (2) also requires a value for the magnification factor M which has been inserted into the program as both a constant $(M = 1.0)$ and as a table. When a tabular value is required, DISCOT is called to determine M by first calculating the A/T and A/B ratios and then interpolating the table for the corresponding value of M. This procedure is repeated in the same manner to obtain values of Q and F. With these values, DERIV calculates the derivatives dA/dN or dB/dN (or both) and transfers these values back to CRANE.

CRANE performs a stepwise integration of the derivatives to determine the changes in the crack parameters A and B, then adds them to the original values. These changed values are then transferred back to the main program and printed out. They are also carried back to subroutine DERIV instead of the original values, and the complete process is repeated until one of two events happens. First, for surface or embedded cracks (fig. 2), if the crack depth becomes equal to or greater than the thickness of the material, the run is terminated. Second, for any type of crack, if the denominator of equation (2) or (3) becomes negative or equal to zero, the integration will become unstable, and the run will be terminated. If neither of these events happens, then the run will continue normally until the final cycle of the last load case has been reached.

## Users' Input Instructions

The first card of the data deck is a title card for the description of the problem. The other cards contain information such as material properties, geometry definition, loading, controls on print and integration interval, and repetition of load spectrum. Detailed instructions for punching data on the cards for each of the flaw types are given below. The order of the data deck is shown in figure 3.

Two-dimensional flaw-growth problems. - The two-dimensional flaw-growth problems are solved by the use of nine cards which are described as follows:

1. Card 1 (one card to a problem)

   This card is a title card for the case being run and may contain up to and including 78 columns of alphanumeric information.

2. Card 2 (one card to a problem)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | Flaw-growth type number | (F10. 0) |

NOTE: If the analysis is for a one-dimensional flaw-growth problem, then 1. 0 goes in this field. If the analysis is for a two-dimensional flaw-growth problem, then 2. 0 goes in this field.

3. Card 3 (one card to a problem)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | AI | (F10. 0) |
| 11 to 20 | T | (F10. 0) |
| 21 to 30 | B | (F10. 0) |

NOTE: Initial flaw dimensions are AI and B.

4. Card 4 (one card to a problem)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | KC | (F10. 0) |
| 11 to 20 | Y | (F10. 0) |
| 21 to 30 | S | (F10. 0) |
| 31 to 40 | G | (F10. 0) |
| 41 to 50 | CA | (E10. 0) |
| 51 to 60 | CB | (E10. 0) |

NOTE: The values for CA and CB are usually very small and should be punched in the following manner. If the value for CA is given as $0.5 \times 10^{-13}$, then it is input as CA = 0. 5 E-13. The E-13 is "right justified" and must end in column 50. The 0. 5 may be punched anywhere (with decimal) between and including columns 41 and 46.

5. Card 5 (one card to a problem)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | NI | (F10. 0) |
| 11 to 20 | DN | (F10. 0) |
| 21 to 30 | START | (F10. 0) |
| 31 to 40 | NL | (I10) |
| 41 to 50 | NBLK | (I10) |

NOTE: The initial cycle number is NI. The desired cycle print interval is DN. START is used to omit the printout up to a cycle number put in for this parameter; then after the START cycle, the printout will be in accordance with the number put in for DN. If the value for NF is put in for START, only AI and the final cycle will be printed. Counters for the program are NL and NBLK. The value given to NL tells the computer when it has read the last of the loading cards (card 9); therefore, the number of 9 cards and the value for NL must agree. The value given to NBLK tells the computer to repeat the number of NL load conditions an NBLK number of times.

6. **Card 6** (one card to a problem)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | IQ | (I10) |
| 11 to 20 | MQTBL | (I10) |
| 21 to 30 | IF | (I10) |
| 31 to 40 | MFTBL | (I10) |

NOTES: (a) The values for both IQ and IF are integers and are used as counters to tell the computer when it has read the last of cards 7 and 8, respectively. Therefore, these values must agree with the number of cards 7 and 8 for the problem. The maximum value of IQ and IF is 100 which means that the user can input a maximum of 100 cards to describe the tables for $\Phi^2$ and F. For a larger number, the program must be changed internally.

(b) MQTBL and MFTBL are also integers and used as flags in the program that eliminate the need for repunching the table of cards 7 and 8 for every problem that uses these identical tables. For example, if several problems require the same $\Phi^2$ and F tables, then these tables will only have to be punched once and presented to the computer in the first problem using the tables. For the first problem or a single problem, the values for MQTBL and MFTBL should be 1 or any value greater than 1. For subsequent problems using these same $\Phi^2$ and F tables, the values of MQTBL and MFTBL will be 0 or left blank.

7. Card 7 (IQ number of these except when MQTBL = 0 or blank)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | AB(I) | (F10. 0) |
| 11 to 20 | QQ(I) | (F10. 0) |

NOTE: If IQ = 1 from card 6, then Q is a constant and the value of Q (not $\Phi^2$) is punched in columns 11 to 20, and the value of AB(I) is omitted. There will only be one card 7 in this case.

8. Card 8 (IF number of these except when MFTBL = 0 or blank)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | AAB(I) | (F10. 0) |
| 11 to 20 | F1(I) | (F10. 0) |

NOTE: The note of card 7 also pertains to this card except replace comments for AB(I) with AAB(I) and QQ(I) with F1(I).

9. Card 9 (NL number of these)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | NF(I) | (F10. 0) |
| 11 to 20 | DP(I) | (F10. 0) |
| 21 to 30 | R(I) | (F10. 0) |
| 31 to 40 | HH(I) | (F10. 0) |
| 41 to 50 | PRC(I) | (F10. 0) |
| 51 to 60 | ISC(I) | (I10) |

NOTES: (a) The initial step size for subroutine CRANE is HH (printed out as H). HH must not equal zero but may be any other value the user chooses. This is a stepwise increment for the integration routine and is usually set to 1. 0 or greater. (By letting HH be equal to a multiple of 10. 0 where HH < (NF-NI)/1000 will usually give satisfactory results with a minimum of computer time.) The step size will be held constant in the program as long as ISC = 1. If the user sets ISC = 0, then the step size will be changed internally when the integration starts to become unstable.

(b) Subroutine CRANE uses precision parameter PRC. This is a positive constant used in the integration routine that is approximately equal to the number of significant decimal digits of local precision. The truncation error comes into play only when the step size flag ISC = 0.

(c) The parameter ISC is an integer and has a value of 1 or 0. If ISC = 1, then the step size (internally) will be held constant through all calculations. If ISC = 0, then the step size will be allowed to vary and become smaller than H as the integration routine starts to become unstable.

One-dimensional flaw-growth problems. - Two typical one-dimensional flaw-growth problems are shown in figure 4. The values of the parameters F, Q, and M for these problems, along with the values for many other problems, can be obtained from reference 12.

With the exceptions of cards 3 and 4, the formats for one-dimensional flaw-growth problems 1 to 9 (fig. 4) are the same as they are for two-dimensional flaw-growth problems. Some input values, however, are different. Since Q will be a constant, IQ is punched as 1 on card 6, and the constant value of Q (e.g., equal to 1.0) should be punched in columns 11 to 20 on card 7. The value of AB(I) should be left blank on card 7 when Q is a constant.

The input values for the factor F depend entirely upon the problem to be solved or the values the program user desires to use (ref. 4). If the value of F is to be a constant, the same procedure described for letting Q be a constant should be used.

Cards 3 and 4 have different formats than those used for two-dimensional flaw-growth problems. The required formats are as follows.

1. Card 3 (one card to a problem)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | AI | (F10.0) |
| 11 to 20 | B | (F10.0) |

2. Card 4 (one card to a problem)

| Column no. | Parameter | Format |
|---|---|---|
| 1 to 10 | KC | (F10.0) |
| 11 to 20 | S | (F10.0) |
| 21 to 30 | CA | (E10.0) |

Values of M for Varying A/T and A/B

The input for the table containing values of M for varying A/T and A/B is somewhat complex, as can be seen from table III. To eliminate the need to input this table for every problem that uses it, the table has been inserted into the main body of the program deck and is called on when required. Those data cards can be seen as cards CRAC 0450 to CRAC 0570 in the main program deck CRACK.

If there is reason to change this table, the user should perform the following steps:

1. Make a new table III or make the necessary changes to the old one.

2. Notice that the A/B ratios in table III and on card CRAC 0450 are increasing; for example: A/B = 0 to A/B = 1.0. (Assumed upper bound values are determined from reference 13.) Similarly, the A/T ratios of table III and card CRAC 0460 are also increasing (A/T = 0 to A/T = 1.0). The table should be input in this manner (both ratios increasing) for use in the interpolation routine of DISCOT.

3. The data for M are then input column by column in the increasing ratio direction. For example, from table III, the first column of M's (for card CRAC 0470) is for the ratio of A/T = 0 and is input from A/B = 0 to A/B = 1.0. The second column (for card CRAC 0480) is for A/T = 0.1 and is input from A/B = 0 to A/B = 1.0. This procedure is repeated for the remaining columns of M.

For this particular table, there is enough room on each card to punch one column of M's per card. It should also be noted that this particular table has 11 rows and 11 columns, thus there will be 121 values of M. If the new table has more values or less values of M, then card CRAC 0440 will have to be changed to agree with this number where IMK = number of values of M in the table.

It should also be noted that the program has been set up for a maximum number of 200 values for M and 100 values each of ratios A/T and A/B. If more values are required to describe the table, then the appropriate changes should be made to the dimension statements of cards CRAC 0030 and CRAC 0040.

## Sample Problem

To provide an example of the use and accuracy of the computer program, a sample problem is furnished along with experimental results for comparison. The sample problem selected is the calculation of fatigue cycles to crack breakthrough of surface-flawed 2219-T87 aluminum alloy plates. This problem is presented because accurate experimental data are available for determining the parameters CA, CB, KC, and S and thus allow a valid comparison with the analytically derived results. Some of this data are shown in figure 5. The data were obtained by putting initial surface cracks in specimens and fatigue loading them at predetermined stress levels and numbers of cycles to obtain small increments of crack growth. The initial and final crack dimensions were determined by pulling the specimens to failure and measuring the dimensions with an optical measuring microscope.

Additional tests were conducted on four specimens to determine the number of cycles required for crack breakthrough to the back face of the specimen. Crack breakthrough was determined by clamping a small chamber filled with water at low pressure on the front side of the specimen and noting when water leaked through to the backside. The results of these tests are presented in table V.

The test results in table V were compared with calculated results from the computer program. The input for the problem and the printed results are given in appendix C. The comparison of experimental and calculated results are shown in figure 6. The comparison is satisfactory, except that the computer results are slightly conservative for all four specimens. The comparison could be improved by adjusting the parameter CA, but figure 5 indicates that this parameter has approximately the correct value. Another cause of the error could be the inaccuracy of the flaw depth correction factor M when applied to thin aluminum specimens. More theoretical and experimental research is required, however, to resolve this difficulty.

The sample problem also assumes that the constant CB is equal to 2CA. This value for CB gives a satisfactory comparison for flaw growth in the width direction. The difference in values between CA and CB is required because the flaw growth on the surface is at a different state of stress than for the growth through the thickness. When analyzing embedded flaws, the state of stress would be the same everywhere at the crack front, and the flaw-growth constants CA and CB should have equal values.

Finally, the sample problem is for a single load level case, or uniform-type fatigue loading. If multiple-load level fatigue is to be analyzed, only cards 5 and 9 are affected. Input instructions for a typical three-load level problem is shown in figure 7.

## CONCLUDING REMARKS

The results of the effort to develop an improved computer analysis for use in fatigue flaw-growth problems can be summarized as follows:

1. A theoretical approach originally developed for one-dimensional or through-the-thickness type cracks has been extended to the analysis of two-dimensional fatigue flaw-growth problems.

2. Using the improved approach, a computer program was developed for predicting fatigue flaw growth of surface, embedded, and through-the-thickness cracks with variable-amplitude fatigue load spectra.

3. The theoretical results compare favorably with test results from surface-flawed specimens of 2219-T87 aluminum alloy.

4. The accuracy of the computer analysis could be improved if less approximate theoretical solutions for the stress-intensity factors of embedded and surface cracks were available.

5. Necessary follow-on work planned includes crack-growth testing and analysis of different structural materials, testing and analysis of complex structural configurations such as integrally stiffened panels, and derivation of a more accurate theoretical solution for the stress-intensity factor of a surface-type flaw.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, February 11, 1972
908-42-38-00-72

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TABLE I. - CORRECTION FACTOR F FOR

EFFECT OF FRONT SURFACE ON

GROWTH THROUGH THE DEPTH

| A/B | F |
|---|---|
| 0 | 1.120 |
| 0.1 | 1.108 |
| .2 | 1.097 |
| .3 | 1.087 |
| .4 | 1.077 |
| .5 | 1.067 |
| .6 | 1.059 |
| .7 | 1.051 |
| .8 | 1.043 |
| .9 | 1.036 |
| 1.0 | 1.030 |
| 2.0 | 1.000 |

TABLE II. - CORRECTION FACTOR G FOR

EFFECT OF FRONT SURFACE ON

GROWTH IN WIDTH DIRECTION

| A/B | G |
|---|---|
| 0.4200 | 1.127 |
| .5000 | 1.121 |
| .5774 | 1.120 |
| .6546 | 1.122 |
| .7338 | 1.108 |
| .8164 | 1.094 |
| 1.0000 | 1.250 |

TABLE III. - VALUES OF M FOR VARYING A/T AND A/B[a]

| A/B \ A/T | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0[c] | 1.000 | 1.005 | 1.021 | 1.048 | 1.091 | 1.155 | 1.250 | 1.400 | 1.667 | 2.294 | 3.100 |
| 0.1 | 1.000 | 1.003 | 1.010 | 1.024 | 1.042 | 1.074 | 1.119 | 1.193 | 1.349 | 1.746 | 2.350 |
| .2 | 1.000 | 1.002 | 1.007 | 1.018 | 1.034 | 1.065 | 1.107 | 1.167 | 1.279 | 1.536 | 1.915 |
| .3 | 1.000 | 1.001 | 1.005 | 1.013 | 1.025 | 1.052 | 1.090 | 1.146 | 1.245 | 1.430 | 1.700 |
| .4 | 1.000 | 1.000 | 1.003 | 1.008 | 1.018 | 1.040 | 1.077 | 1.131 | 1.217 | 1.361 | 1.580 |
| .5 | 1.000 | 1.000 | 1.001 | 1.006 | 1.014 | 1.030 | 1.065 | 1.110 | 1.190 | 1.320 | 1.530 |
| .6 | 1.000 | 1.000 | 1.000 | 1.005 | 1.010 | 1.025 | 1.051 | 1.093 | 1.168 | 1.291 | 1.490 |
| .7 | 1.000 | 1.000 | 1.000 | 1.004 | 1.008 | 1.019 | 1.043 | 1.082 | 1.148 | 1.265 | 1.455 |
| .8 | 1.000 | 1.000 | 1.000 | 1.003 | 1.006 | 1.013 | 1.035 | 1.072 | 1.131 | 1.241 | 1.420 |
| .9 | 1.000 | 1.000 | 1.000 | 1.002 | 1.004 | 1.010 | 1.029 | 1.062 | 1.117 | 1.220 | 1.390 |
| 1.0 | 1.000 | 1.000 | 1.000 | 1.001 | 1.003 | 1.008 | 1.024 | 1.052 | 1.102 | 1.199 | 1.360 |

[a]Values determined from Shah's and Kobayashi's solution.

[b]Values determined by extrapolating Shah's and Kobayashi's solution.

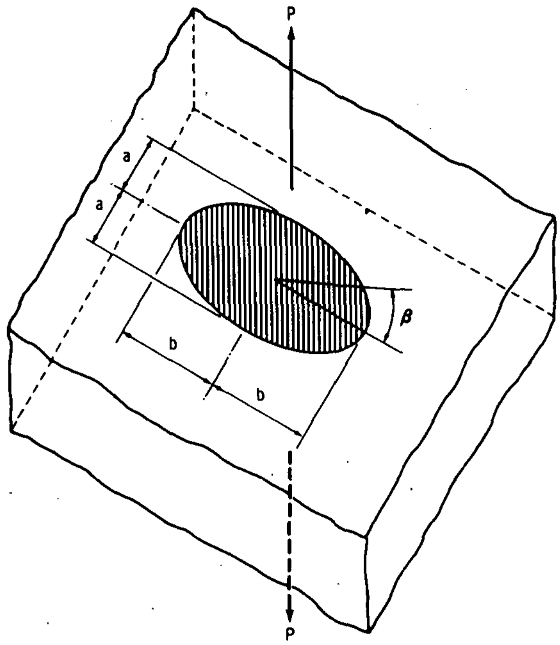
[c]Assumed upper bound values determined from reference 13 solution where $M = 1/(1-A^2/B^2)^{1/2}$.

TABLE IV. - VALUES OF A/B OR B/A COMPARED WITH $\Phi^2$

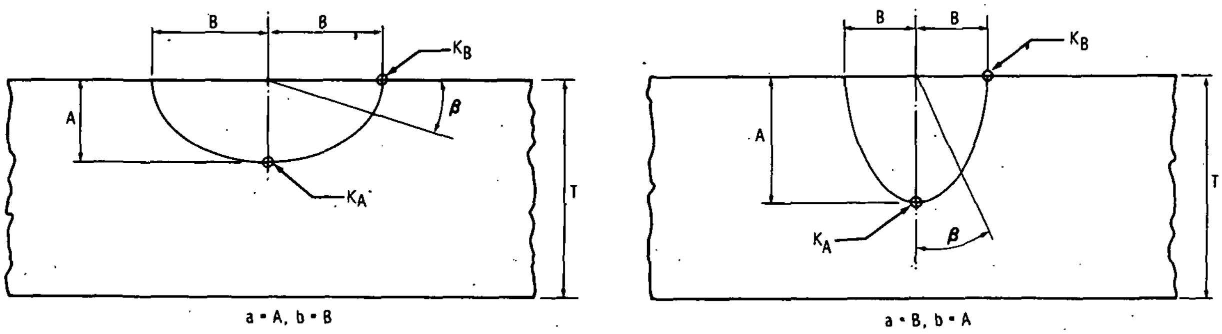
| A/B or B/A | $\Phi^2$ |
|---|---|
| 0.00000 | 1.000000 |
| 0.22361 | 1.124605 |
| .31622 | 1.220527 |
| .38729 | 1.307354 |
| .44721 | 1.388838 |
| .50000 | 1.466656 |
| .54772 | 1.541746 |
| .59161 | 1.614772 |
| .63245 | 1.685915 |
| .67082 | 1.755688 |
| .70710 | 1.824239 |
| .74162 | 1.891730 |
| .77459 | 1.958297 |
| .80622 | 2.024049 |
| .83666 | 2.089074 |
| .86602 | 2.153444 |
| .89443 | 2.217225 |
| .92195 | 2.280468 |
| .94868 | 2.343220 |
| .97468 | 2.405517 |
| 1.00000 | 2.467400 |

TABLE V. - RESULTS OF CRACK BREAKTHROUGH TESTS OF SURFACE-FLAWED 2219-T87 ALUMINUM PLATES FATIGUE LOADED IN 70° F DISTILLED WATER

| Specimen number | T | | Initial flaw size | | | | Final flaw width, $B_f$ | | Fatigue loading | | | Cycles to crack breakthrough |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $A_i$ | | $B_i$ | | | | DP | | R | |
| | mm | in. | mm | in. | mm | in. | mm | in. | (MN/$m^2$) | ksi | | |
| 9L | 3.198 | 0.1259 | 1.68 | 0.066 | 3.150 | 0.1240 | 4.635 | 0.1825 | 134.9 | 19.57 | 0.01 | 18 065 |
| 10L | 3.162 | .1245 | 1.70 | .067 | 3.213 | .1265 | 4.508 | .1775 | 190.9 | 27.69 | .01 | 5 272 |
| 12M | 3.187 | .1255 | 1.65 | .065 | 3.340 | .1315 | 4.635 | .1825 | 217.5 | 31.54 | .01 | 3 770 |
| 14M | 3.030 | .1193 | 1.60 | .063 | 3.264 | .1285 | 4.648 | .1830 | 285.8 | 41.45 | .01 | 1 420 |

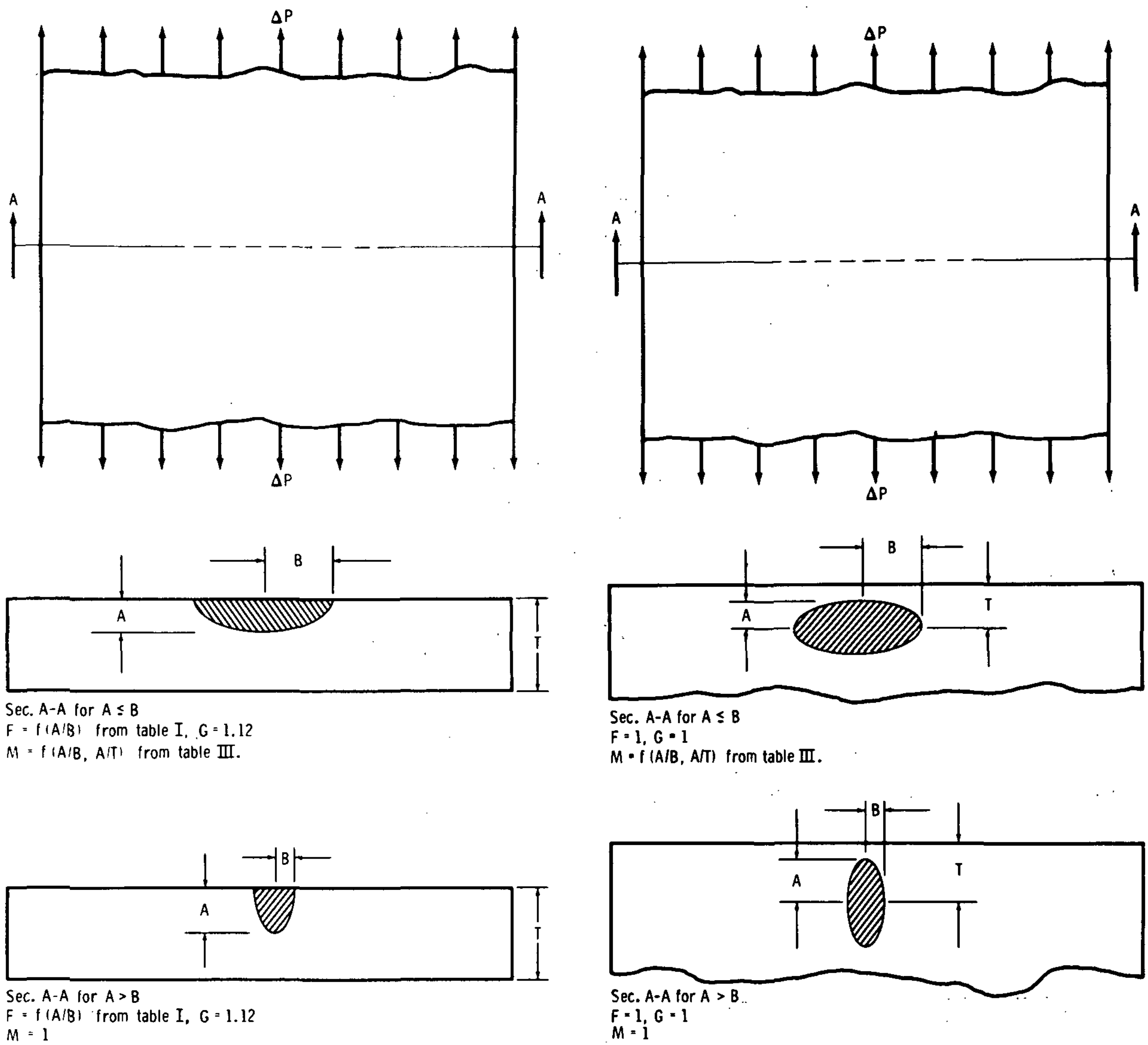



(a) Elliptical crack in an infinite body.




(b) Semielliptical crack where $A \leq B$. (c) Semielliptical crack where $A > B$.

Figure 1. - Assumed geometry for an elliptical crack in an infinite-thickness body and a semielliptical crack in a finite-thickness body.




(a) Surface flaw.

(b) Embedded flaw.

Figure 2. - Crack geometry for surface and embedded flaws.

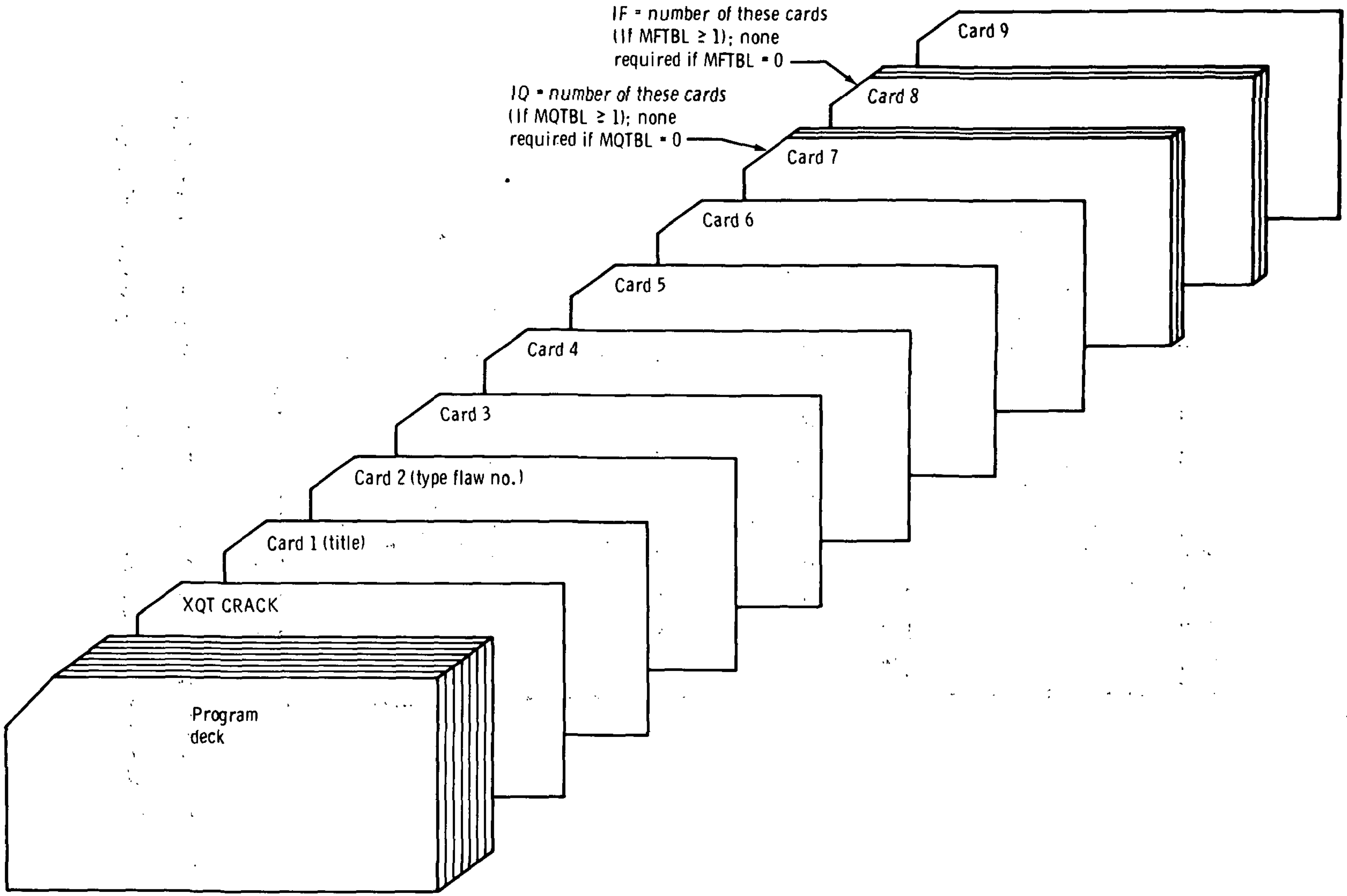
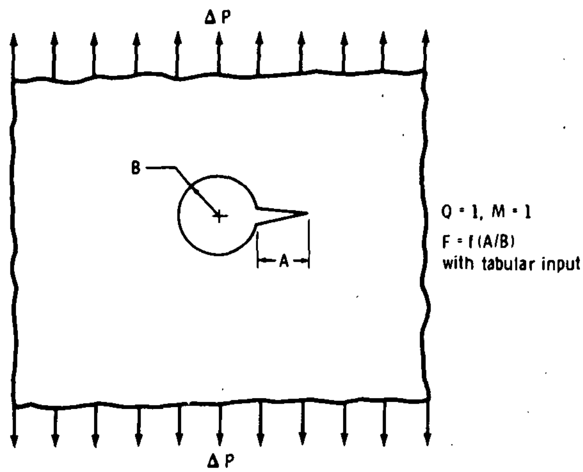
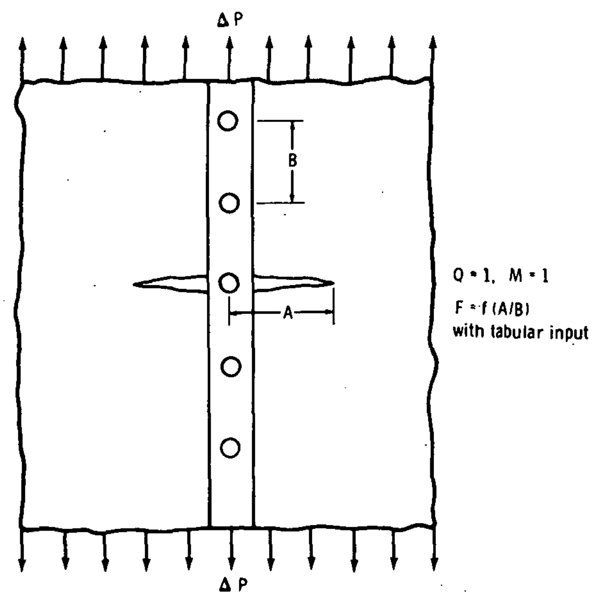



Figure 3. - Order of program and data deck.




(a) Crack propagating from hole.




(b) Symmetric crack propagating from rivet hole in stiffened plate.

Figure 4. - Typical one-dimensional flaw-growth problems.

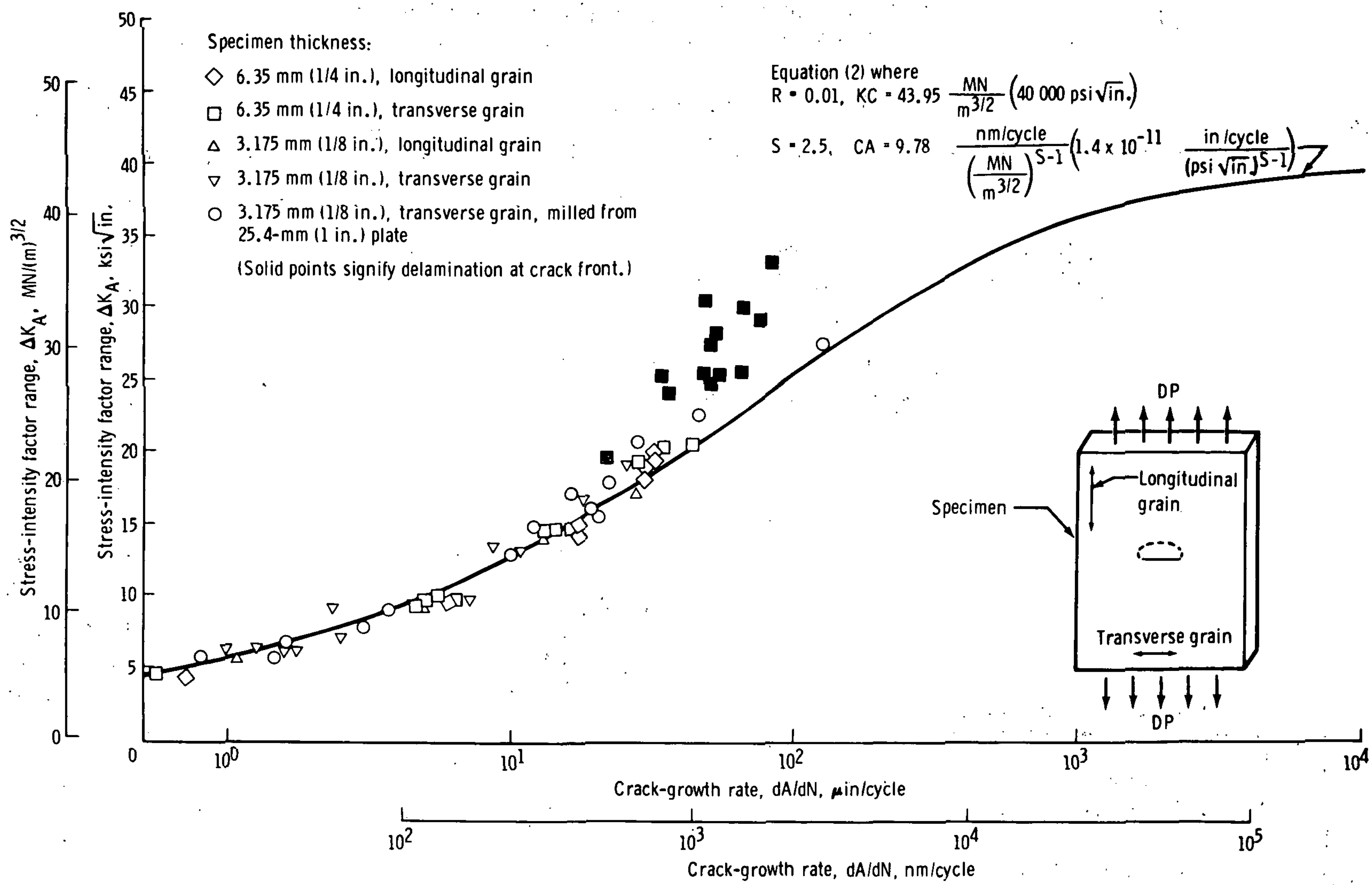



Figure 5. - Comparison of theoretical crack-growth rate with experimental room temperature data for 2219-T87 aluminum plate material.

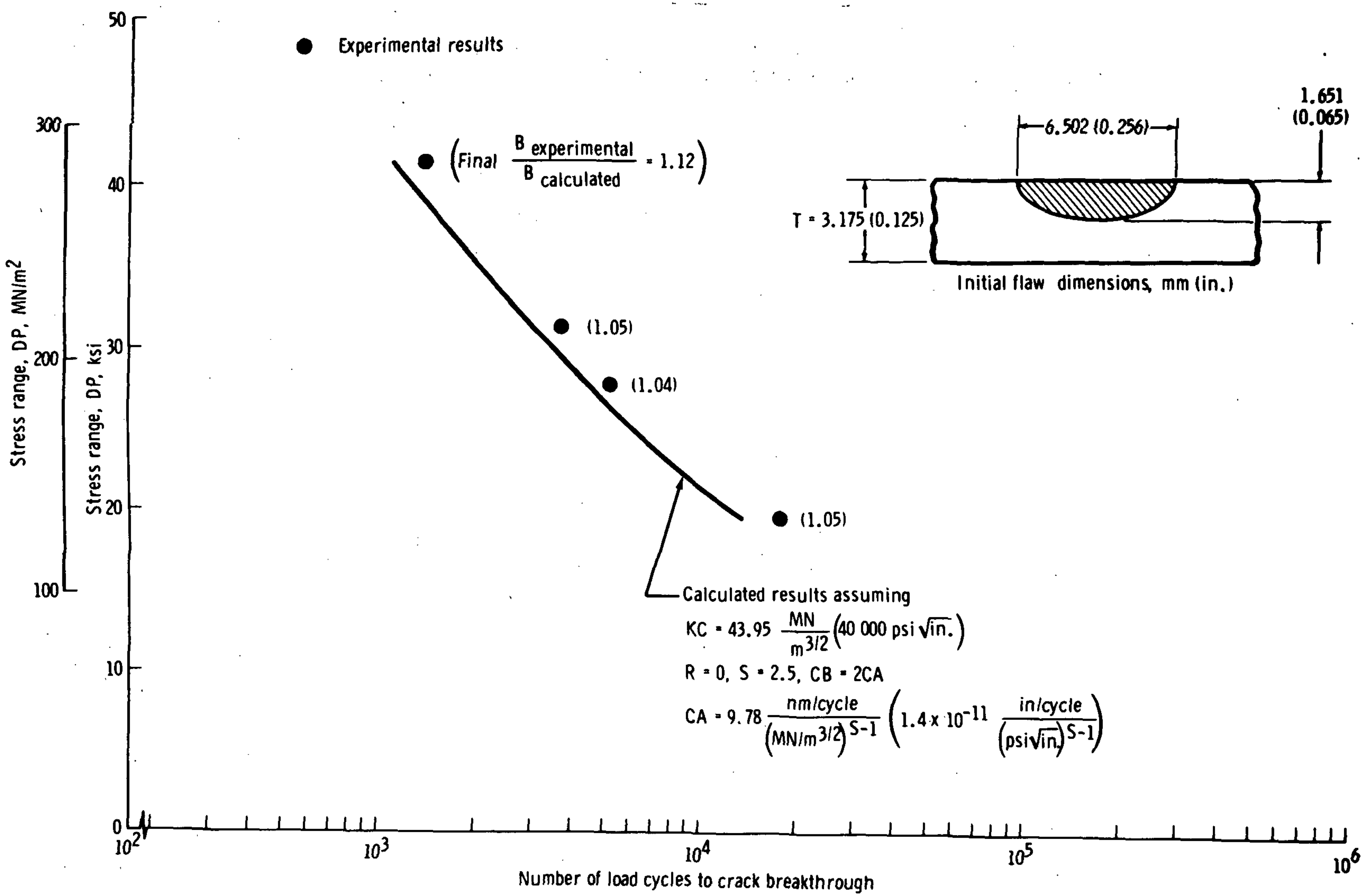



Figure 6. - Comparison of experimental results with calculated results for load cycles to crack breakthrough in 2219-T87 aluminum alloy sheet.

INPUT INSTRUCTIONS

CARD 5:

NI = 0.0
DN = 100.
START = 0.0
NL = 3
NBLK = 1

CARD 9 (1):

NF = 2000. (cycles)
DP = 20000. (psi)
R = 0.0
HH = 1.0
PRC = 7.0
ISC = 1

CARD 9 (2):

NF = 4000.
DP = 10000.
R = .666
HH = 1.0
PRC = 7.0
ISC = 1

CARD 9 (3):

NF = 5500.
DP = 10000.
R = .5
HH = 1.0
PRC = 7.0
ISC = 1

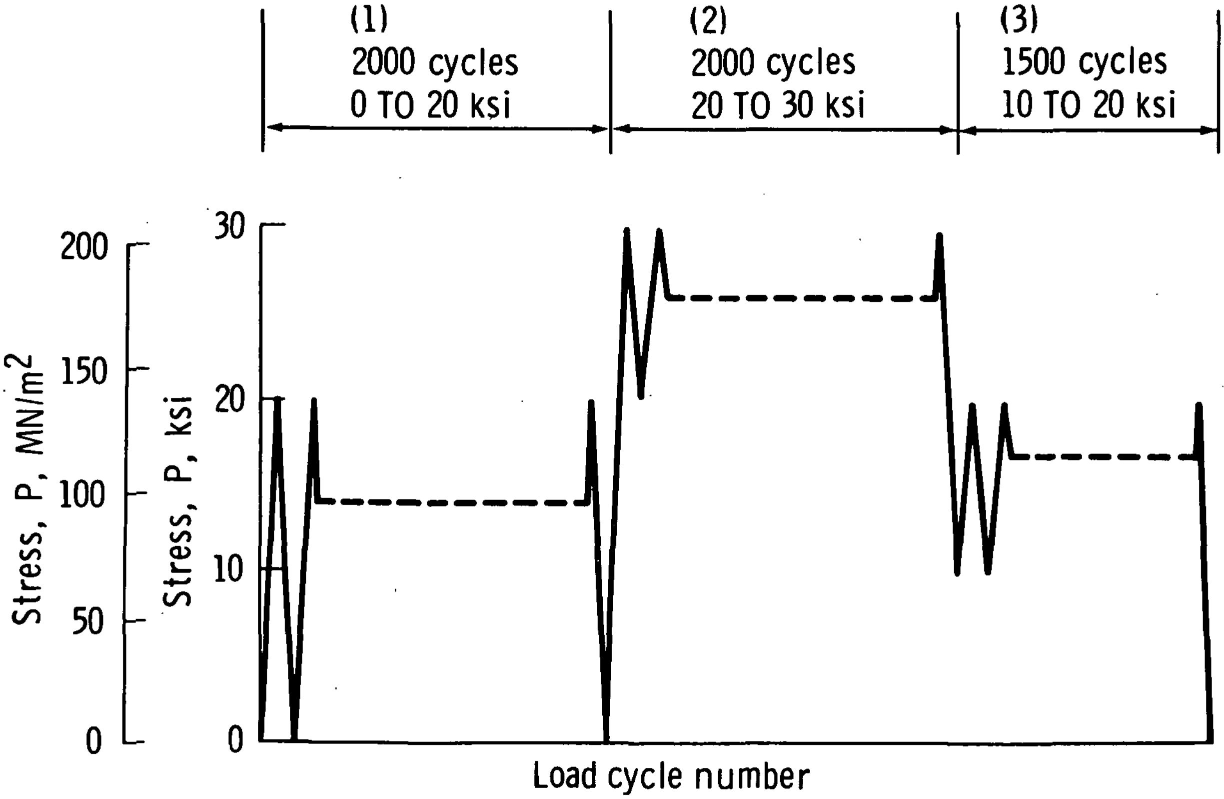



**Figure 7. - Input instructions for a typical multiple-load level program.**

## APPENDIX A

## CONVERSION OF U. S. CUSTOMARY UNITS TO SI UNITS

The SI was adopted by the Eleventh General Conference of Weights and Measures, Paris, October 1960, in Resolution Number 12 (ref. 14).

TABLE A-I. - CONVERSION FACTORS FOR SI UNITS

| To convert from U. S. Customary Units | Multiply by — | To obtain SI units |
|---|---|---|
| lbf | 4.448222 | newtons (N) |
| in. | $2.54 \times 10^{-2}$ | meters (m) |
| kips per square inch (ksi) | $6.894757 \times 10^{6}$ | newtons/meter$^2$ (N/m$^2$) |
| ksi $\sqrt{\text{in.}}$ | 1.0988 | MN/(m)$^{3/2}$ |
| $\mu$in/cycle | 25.4 | nm/cycle |

TABLE A-II. - PREFIXES AND SYMBOLS TO INDICATE MULTIPLES OF UNITS

| Multiple | Prefix | Symbol |
|---|---|---|
| $10^{-9}$ | nano | n |
| $10^{-6}$ | micro | $\mu$ |
| $10^{-3}$ | milli | m |
| $10^{6}$ | mega | M |

# APPENDIX B

# COMPUTER PROGRAM LISTING

```
 $ FOR CRACK                                                            CRAC0000
      DIMENSION  TITLE(13)                                              CRAC0010
      DIMENSION MH(100), PRC(100), ISC(100)                             CRAC0020
      DIMENSION MMK(200), AB(100), QQ(100), AT(100),  R(100), DR(100),  CRAC0030
     1    NF(100),ABM(100),F1(100),AAB(100)                             CRAC0040
      REAL MF,NI,KC,MMK,M                                               CRAC0050
      COMMON /CRANEC/XN,A(40),FF(40),H,N,BB(40),MIN,PREC,IDENT,INIT     CRAC0060
      COMMON /CRAC/ K,B,T,IMK,IQ,AB,AT,MMK,QQ,DR,R,S,KC,CA,G,DENOM1     CRAC0070
     1,Y,A1,DENOM2,DK1,DK2,Q,ADT,ADR,M,ABM,F1,IF,AAB,TYPE,F,CB          CRAC0080
  500 READ(5,6969) TITLE                                                CRAC0090
      FF(1) = 0.0                                                       CRAC0091
      FF(2) = 0.0                                                       CRAC0092
 6969 FORMAT(13A6)                                                      CRAC0100
      WRITE(6,6970) TITLE                                               CRAC0110
 6970 FORMAT (1H1,21X13A6//)                                            CRAC0120
      READ(5,3) TYPE                                                    CRAC0130
    3 FORMAT(F10.0)                                                     CRAC0140
      IF(TYPE.LT.2.0) GO TO 7                                           CRAC0150
      READ(5,1)AI,T,B,KC,Y,S,G,CA,CB,NI,DN,START,NL,NBLK,IQ,MQTBL,      CRAC0160
     1IF,MFTBL                                                          CRAC0170
    1 FORMAT(3F10.0/4F10.0,2E10.0/3F10.0,2I10/4I10)                     CRAC0180
      WRITE(6,2)AI,T,B,KC,Y,S,G,CA,CB,NI,DN,NL,NBLK,IQ,IF               CRAC0190
    2 FORMAT(45X'CRACK PROPAGATION STUDY'///55X'INPUT'//30X'INITIAL CRACCRAC0200
     1K DEPTH',11X'AI ='E20.8/30X'PLATE THICKNESS',15X'T  ='E20.8/30X'INCRAC0210
     2ITIAL CRACK WIDTH',11X'B  ='E20.8/30X'FRACTURE TOUGHNESS',12X'KC =CRAC0220
     3'E20.8/30X'MATERIAL YIELD STRESS',9X'Y  ='E20.8/30X'EXPONENT OF DKCRAC0230
     4',16X'S  ='E20.8/30X'CORRECTION FACTOR',13X'G  ='E20.8/30X'MATERIACRAC0240
     5L CONSTANT FOR A',7X'CA ='E20.8/30X'MATERIAL CONSTANT FOR B',     CRAC0250
     67X'CB ='E20.8/30X'INITIAL CYCLE NUMBER',10X'NI ='E20.8/           CRAC0260
     730X'CYCLE PRINT INTERVAL',10X'DN ='E20.8/30X'NUMBER LOAD CONDITIONCRAC0270
     8S',8X'NL ='I20/30X'NUMBER LOAD BLOCKS',12X'LDS='I20/              CRAC0280
     930X'NUMBER OF Q VALUES',12X'IQ ='I20/                             CRAC0290
     130X'NUMBER OF F VALUES',12X'IF ='I20//)                           CRAC0300
      GO TO 94                                                          CRAC0310
    7 READ(5,5)AI,B,KC,S,CA,NI,DN,START,NL,NBLK,IQ,MQTBL,IF,MFTBL       CRAC0320
    5 FORMAT(2F10.0/2F10.0,E10.0/3F10.0,2I10/4I10)                      CRAC0330
      WRITE(6,13)AI,B,KC,S,CA,NI,DN,NL,NBLK,IQ,IF                       CRAC0340
   13 FORMAT(45X'CRACK PROPAGATION STUDY'///55X'INPUT'//30X'INITIAL CRACCRAC0350
     1K DEPTH',11X'AI ='E20.8/30X'INITIAL CRACK WIDTH',11X'B  ='E20.8/  CRAC0360
     230X'FRACTURE TOUGHNESS',12X'KC ='E20.8/                           CRAC0370
     3              30X'EXPONENT OF DK',16X'S  ='E20.8/30X'MATERIAL CONSCRAC0380
     4TANT',13X'CA ='E20.8/30X'INITIAL CYCLE NUMBER',10X'NI ='E20.8/    CRAC0390
     530X'CYCLE PRINT INTERVAL',10X'DN ='E20.8/30X'NUMBER LOAD CONDITIONCRAC0400
     6S',8X'NL ='I20/30X'NUMBER LOAD BLOCKS',12X'LDS='I20/              CRAC0410
```

```
     730X'NUMBER OF Q VALUES',12X'IQ ='I20/30X'NUMBER OF F VALUES',12X   CRAC0420
     8'IF ='I20//)                                                       CRAC0430
  94 INK = 121                                                           CRAC0440
     DATA(ABM(I),I=1,11)/0.0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0/    CRAC0450
     DATA(AT(I),I=1,11)/0.0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0/     CRAC0460
     DATA(AMK(I),I=1,121)/1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,              CRAC0470
    11.005,1.003,1.002,1.001,1.,1.,1.,1.,1.,1.,1.,                       CRAC0480
    21.021,1.01,1.007,1.005,1.003,1.001,1.,1.,1.,1.,1.,                  CRAC0490
    31.048,1.024,1.018,1.013,1.008,1.006,1.005,1.004,1.003,1.002,1.001,CRAC0500
    41.091,1.042,1.034,1.025,1.018,1.014,1.01,1.008,1.006,1.004,1.003,  CRAC0510
    51.155,1.074,1.065,1.052,1.04,1.03,1.025,1.019,1.013,1.01,1.008,     CRAC0520
    61.25,1.119,1.107,1.09,1.077,1.065,1.051,1.043,1.035,1.029,1.024,    CRAC0530
    71.4,1.193,1.167,1.146,1.131,1.11,1.093,1.082,1.072,1.062,1.052,     CRAC0540
    81.667,1.349,1.279,1.245,1.217,1.19,1.168,1.148,1.131,1.117,1.102,  CRAC0550
    92.294,1.746,1.536,1.43,1.361,1.32,1.291,1.265,1.241,1.22,1.199,     CRAC0560
    13.1,2.35,1.915,1.7,1.58,1.53,1.49,1.455,1.42,1.39,1.36/             CRAC0570
     NL = NL + 1                                                         CRAC0580
     IF(MQTBL.LE.0) GO TO 27                                             CRAC0590
     READ(5,25)(AB(I),QQ(I),I=1,IQ)                                      CRAC0600
  25 FORMAT(2F10.0)                                                      CRAC0610
     IF(IQ.GT.1) GO TO 26                                                CRAC0620
     WRITE(6,29) QQ(1)                                                   CRAC0630
  29 FORMAT(//20X'NOTE-- Q IS A CONSTANT ='E15.8/)                       CRAC0640
     GO TO 61                                                            CRAC0650
  27 WRITE(6,28)                                                         CRAC0660
  28 FORMAT(//20X'NOTE-- THE A/B OR B/A VS. PHI(SQUARED) TABLE FOR THISCRAC0670
    1 CASE IS THE SAME AS THE PRECEEDING CASE'/)                         CRAC0680
     GO TO 61                                                            CRAC0690
  26 WRITE(6,35) (AB(I),QQ(I),I=1,IQ)                                    CRAC0700
  35 FORMAT (//43X'A/B OR B/A'9X'PHI(SQUARED)'//(34X2E20.8/))            CRAC0710
  61 CONTINUE                                                            CRAC0720
     IF(MFTBL.LE.0) GO TO 55                                             CRAC0730
     READ(5,56)(AAB(I),F1(I),I=1,IF)                                     CRAC0740
  56 FORMAT(2F10.0)                                                      CRAC0750
     IF(IF.GT.1) GO TO 60                                                CRAC0760
     WRITE(6,57) F1(1)                                                   CRAC0770
  57 FORMAT(//20X'NOTE-- CORRECTION FACTOR F IS A CONSTANT ='E15.8/)     CRAC0780
     GO TO 62                                                            CRAC0790
  55 WRITE(6,58)                                                         CRAC0800
  58 FORMAT(//20X'NOTE-- THE A/B VS. F TABLE FOR THIS CASE IS THE SAME   CRAC0810
    1AS THE PRECEEDING CASE'/)                                           CRAC0820
     GO TO 62                                                            CRAC0830
  60 WRITE(6,59)(AAB(I),F1(I),I=1,IF)                                    CRAC0840
  59 FORMAT(//47X'A/B',20X'F'//(34X2E20.8/))                             CRAC0850
```

```
   62 CONTINUE                                                        CRAC0860
      READ (5,4) (NF(I),DP(I),R(I),HH(I),PRC(I),ISC(I),I=2,NL)        CRAC0870
    4 FORMAT (5F10.0,I10)                                             CRAC0880
      DO 20 JB=1,NBLK                                                 CRAC0890
      IF(JB.EQ.1) GO TO 30                                            CRAC0900
      WRITE(6,101) JB                                                 CRAC0901
  101 FORMAT(//55X'OUTPUT'/48X'BLOCK LOAD NO.'I5/)                    CRAC0902
      AI = A(1)                                                       CRAC0910
      B = A(2)                                                        CRAC0920
   30 CONTINUE                                                        CRAC0930
      NF(1) = NI                                                      CRAC0940
      IF(JB.GT.1) GO TO 102                                           CRAC0941
      WRITE (6,6) JB                                                  CRAC0950
    6 FORMAT (1H1,55X'OUTPUT' /48X'BLOCK LOAD NO.' I5/)               CRAC0960
  102 IQUIT = 0                                                       CRAC0970
      A(1) = AI                                                       CRAC0980
      A(2) = B                                                        CRAC0990
      DO 20 K=2,NL                                                    CRAC1000
      H = HH(K)                                                       CRAC1010
      PREC = PRC(K)                                                   CRAC1020
      IDONT = ISC(K)                                                  CRAC1030
      PT = -H                                                         CRAC1040
      N = 2                                                           CRAC1050
      IF(TYPE.LT.2.0) N=1                                             CRAC1051
      NB (1) = 0                                                      CRAC1060
      NB(2) = 0                                                       CRAC1070
      MIN = 3                                                         CRAC1080
      IP = 1                                                          CRAC1090
      INIT = 0                                                        CRAC1100
      XN = NF(K-1)                                                    CRAC1110
      IF (NF(K) .GT. NF(K-1)) GO TO 8                                 CRAC1120
      XN = NI                                                         CRAC1130
      A(1) = AI                                                       CRAC1140
      A(2) = B                                                        CRAC1150
      GO TO 9                                                         CRAC1160
    8 IF (IQUIT .EQ. 1) GO TO 500                                     CRAC1170
    9 CONTINUE                                                        CRAC1180
      IF(JB.GT.1) GO TO 47                                            CRAC1190
      WRITE (6,17)NF(K),DP(K),R(K),H,PREC,IDONT,START                 CRAC1200
   17 FORMAT (//1X'FINAL CYCLE NUMBER',7X'NF ='E20.8/1X'CYCLIC STRESS RACRAC1210
     1NGE',6X'DP ='E20.8/1X'CYCLIC STRESS RATIO',6X'R  ='E20.8/1X'STEP SCRAC1220
     2IZE',16X'H  ='E20.8/1X'PRECISION',16X'PRC='E20.8/1X'STEP CHANGE', CRAC1230
     314X'ISC='I20/1X'START CYCLE PRINT',8X'START='F18.8//)           CRAC1240
      IF(TYPE.LT.2.0) GO TO 82                                        CRAC1250
```

```
      WRITE(6,80)                                                       CRAC1260
   80 FORMAT(9X'N',14X'A',14X'B',12X'DA/DN',10X'DB/DN',10X'DK(A)',      CRAC1270
     110X'DK(B)',12X'Q'//)                                              CRAC1280
      GO TO 10                                                          CRAC1290
   82 WRITE(6,83)                                                       CRAC1300
   83 FORMAT(9X'N',14X'A',12X'DA/DN',10X'DK(A)',13X'F'//)               CRAC1310
      GO TO 10                                                          CRAC1320
   47 IF(K.GT.2 .AND. JB.GT.1) GO TO 10                                 CRAC1321
      IF(TYPE.LT.2.0) GO TO 84                                          CRAC1330
      WRITE(6,80)                                                       CRAC1340
      GO TO 10                                                          CRAC1350
   84 WRITE(6,83)                                                       CRAC1360
      GO TO 10                                                          CRAC1370
   11 IP = 0                                                            CRAC1380
   10 IF (XN .GE. NF(K)) GO TO 19                                       CRAC1390
      PT = PT + H                                                       CRAC1400
      CALL CRANE                                                        CRAC1410
      IF(TYPE.LT.2.0) GO TO 95                                          CRAC1420
      IF (A(1).GE.T) GO TO 21                                           CRAC1430
      IF(DENOM1.GT.0.0 .AND. DENOM2.GT.0.0) GO TO 15                    CRAC1440
      GO TO 21                                                          CRAC1450
   95 IF(DENOM1.GT.0.0) GO TO 15                                        CRAC1460
   21 CONTINUE                                                          CRAC1470
      IQUIT = 1                                                         CRAC1480
      GO TO 19                                                          CRAC1490
   15 IF(JB.GT.1) GO TO 71                                              CRAC1491
      IF(XN.LE.0.0) GO TO 70                                            CRAC1500
      GO TO 71                                                          CRAC1510
   70 IF(TYPE.LT.2.0) GO TO 73                                          CRAC1520
      WRITE(6,16)XN,A(1),A(2),FF(1),FF(2),DK1,DK2,Q                     CRAC1530
      GO TO 71                                                          CRAC1540
   73 WRITE(6,86)XN,A(1),FF(1),DK1,F                                    CRAC1550
   71 IF (PT .LT. DN) GO TO 11                                          CRAC1560
      IF(IP.EQ.1) GO TO 18                                              CRAC1570
      IF(XN .LT. START) GO TO 18                                        CRAC1580
      IF(TYPE.LT.2.0) GO TO 85                                          CRAC1590
      WRITE (6,16)XN,A(1),A(2),FF(1),FF(2),DK1,DK2,Q                    CRAC1600
   16 FORMAT (1X,8E15.8)                                                CRAC1610
      GO TO 18                                                          CRAC1620
   85 WRITE(6,86)XN,A(1),FF(1),DK1,F                                    CRAC1630
   86 FORMAT(1X,5E15.8)                                                 CRAC1640
   18 IF (XN .GE. NF(K)) GO TO 20                                       CRAC1650
      PT = 0.0                                                          CRAC1660
      GO TO 11                                                          CRAC1670
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19 IF(TYPE.LT.2.0) GO TO 87                                          CRAC1680
   WRITE (6,16) XN,A(1),A(2),FF(1),FF(2),DK1,DK2,Q                   CRAC1690
   GO TO 20                                                          CRAC1700
87 WRITE(6,86)XN,A(1),FF(1),DK1,F                                    CRAC1710
20 CONTINUE                                                          CRAC1720
   GO TO 500                                                         CRAC1730
   END                                                               CRAC1740

@ FOR DERIV                                                          DERI0000
   SUBROUTINE DERIV                                                  DERI0010
   DIMENSION MMK(200), AB(100), QQ(100), AT(100),  R(100), DP(100)  DERI0020
  1,ABM(100),F1(100),AAB(100)                                        DERI0030
   REAL M,KC,MMK                                                     DERI0040
   COMMON /CRANEC/XN,A(40),FF(40),H,N,UB(40),MIN,PRFC,IDCNT,INIT     DERI0050
   COMMON /CRAC/ K,B,T,IMK,IQ,AB,AT,MMK,QQ,DP,R,S,KC,CA,G,DENOM1     DERI0060
  1,Y,A1,DENOM2,DK1,DK2,Q,ADT,ADB,M,ABM,F1,IF,AAB,TYPE,F,CB          DERI0070
   AA = A(1)                                                         DERI0080
   BB = A(2)                                                         DERI0090
   M = 1.0                                                           DERI0100
   IF(TYPE.LT.2.0) GO TO 10                                          DERI0110
   ADT = AA/T                                                        DERI0120
   ADB = AA/BB                                                       DERI0130
   IF(BB.LT.AA) ADB=BB/AA                                            DERI0140
   IF(G.LE.1.0) GO TO 5                                              DERI0150
   IF(AA.LE.BB) CALL DISCOT(ADB,ADT,ABM,MMK,AT,+022,IMK,11,M)        DERI0160
   Q = QQ(1)                                                         DERI0170
   IF(IQ.GT.1) CALL DISCOT(ADB,ADB,AB,QQ,QQ,-020,IQ,0,Q)             DERI0180
   IF(IQ.GT.1) Q=Q-0.212*(DP(K)/(Y*(1.0-R(K))))**2                   DERI0190
   AOB = AA/BB                                                       DERI0200
   F = 1.0                                                           DERI0210
   IF(AOB.LE.2.0) CALL DISCOT(AOB,AOB,AAB,F1,F1,-020,IF,0,F)         DERI0220
   GO TO 20                                                          DERI0230
 5 IF(AA.LE.BB) CALL DISCOT(ADB,ADT,ABM,MMK,AT,+022,IMK,11,M)        DERI0240
   Q = QQ(1)                                                         DERI0250
   IF(IQ.GT.1) CALL DISCOT(ADB,ADB,AB,QQ,QQ,-020,IQ,0,Q)             DERI0260
   IF(IQ.GT.1) Q=Q-0.212*(DP(K)/(Y*(1.0-R(K))))**2                   DERI0270
   F = F1(1)                                                         DERI0280
20 DK1 = F*DP(K)*BB/AA*SQRT(3.1415926*AA/Q)                          DERI0290
   IF(AA.LE.BB) DK1 = F*M*DP(K)*SQRT(3.1415926*AA/Q)                 DERI0300
   DK2 = G*DP(K)*SQRT(3.1415926*BB/Q)                                DERI0310
   IF(AA.LE.BB) DK2 = G*DP(K)*SQRT(3.1415926*BB/Q)*(AA/BB)           DERI0320
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```
      DENOM1=(1.0-R(K))*KC-DK1                                          DERI0330
      FF(1)=CA*DK1**S/DENOM1                                            DERI0340
      DENOM2=(1.0-R(K))*KC-DK2                                          DERI0350
      FF(2)=CB*DK2**S/DENOM2                                            DERI0360
      GO TO 25                                                          DERI0370
   10 AOB = AA/BB                                                       DERI0380
      F = 1.0                                                           DERI0390
      IF(AOB.LE.2.0) CALL DISCOT(AOB,AOB,AAB,F1,F1,-020,IF,0,F)         DERI0400
      Q = QQ(1)                                                         DERI0410
      DK1 = F*DP(K)*M*SQRT(3.1415926*AA/Q)                              DERI0420
      DENOM1 = (1.0-R(K))*KC-DK1                                        DERI0430
      FF(1)=CA*DK1**S/DENOM1                                            DERI0440
   25 RETURN                                                            DERI0450
      END                                                               DERI0460

@ FOR CRANE                                                             CRAN0000
      SUBROUTINE CRANE                                                  CRAN0010
C     THE ARGUMENTS OF THIS SUBROUTINE ARE ALL CONTAINED IN THE FOLLOW- CRAN0020
C     ING COMMON STATEMENT, LABELED CRANEC.  DRIVER PROGRAM MUST CONFORMCRAN0030
C     IN ORDER AND DIMENSIONS WITHIN COMMON/CRANEC/,THOUGH NOT NECES-   CRAN0040
C     SARILY IN THE NAMES OF THE VARIABLES                              CRAN0050
C                                                                       CRAN0060
      COMMON/CRANEC/X,Y(40),F(40),H,N,NB(40),MIN,PREC,IDONT,INIT        CRAN0070
C                                                                       CRAN0080
C        MEANING OF THE ARGUMENTS ARE AS FOLLOWS                        CRAN0090
C     X      THE INDEPENDENT VARIABLE.                                  CRAN0100
C     Y      ARRAY OF DEPENDENT VARIABLES, 40 MAXIMUM.                  CRAN0110
C     F      ARRAY OF DERIVATIVES, FUNCTIONS OF X AND THE Y VECTOR.     CRAN0120
C     H      STEP SIZE IN X.  MUST BE NON-ZERO.  USUALLY MAY BE ALTERED CRAN0130
C            INTERNALLY BY CRANE, AFTER FIRST BEING SET + OR - EXTERNALLY.CRAN0140
C     N      THE NO. OF Y S AND F S IN THE SYSTEM.  USUALLY THE NO. ALSO CRAN0150
C            OF COUPLED ORDINARY DIFF. EQUNS.                           CRAN0160
C     NB     AN ARRAY OF FLAGS.  IF +, HOLD ABSOLUTE TRUNCATION ERROR EST.CRAN0170
C                                    BELOW A SPECIFIED LIMIT =10.**(-PREC) CRAN0180
C                                IF 0, DITTO FOR RELATIVE TRUNCATION ERRORCRAN0190
C                                    ESTIMATE.                          CRAN0200
C                                IF -, DISREGARD THE TRUNC. ERROR. EST. CRAN0210
C                                    FOR THE Y S WHOSE FLAGS ARE NEGATIVE. CRAN0220
C     MIN    THE MINIMUM NO. OF STEPS BETWEEN OCCASIONS FOR DOUBLING H. CRAN0230
C            THE VALUE OF MIN MAY NOT EXCEED 10, NOR BE LESS THAN 3.    CRAN0240
C     INIT SET TO ZERO BEFORE FIRST CALL, CAUSING THE SR TO INITIALIZE  CRAN0250
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C         ITSELF.  THEREAFTER, INIT IS BUMPED  INTERNALLY, EACH STEP.  CRAN0260
C     IDONT A FLAG WHICH IF NON-ZERO, FORBIDS ANY CHANGE IN H TO BE      CRAN0270
C         MADE INTERNALLY BY THE SP.                                     CRAN0280
C     PREC A POSITIVE CONST. APPROXIMATELY EQUAL TO THE NO. OF SIGNIFI- CRAN0290
C         CANT DECIMAL DIGITS OF LOCAL PRECISION.  (BASED ON TRUNCATIONCRAN0300
C         ERROR ESTIMATES MADE INTERNALLY.  EFFECTIVE ONLY IF IDONT=0.)CRAN0310
C                                                                        CRAN0320
C        THE PARTICULAR PREDICTOR-CORRECTOR ALGORITHM IS THAT PUBLISHED CRAN0330
C     BY CRANE AND KLOPFENSTEIN IN J.A.C.M. VOL 12, PAGES 227-241, APRILCRAN0340
C     1965.  IT IS OF FOURTH ORDER, I.E., TRUNCATION ERRORS ARE OF ORDERCRAN0350
C     H**5.  THE ALGORITHM WAS DEVELOPED TO MAXIMIZE THE RANGE OF STEP  CRAN0360
C     SIZE CONSISTENT WITH ABSOLUTE STABILITY, AND IN A LOOSER SENSE, TOCRAN0370
C     HAVE A GOOD RANGE OF RELATIVE STABILITY.  THESE RANGES, EXPRESSED CRAN0380
C     AS H,NORMALIZED BY MULTIPLYING BY PARTIAL DERIV OF Y(=G(X,Y)) WITHCRAN0390
C     RESPECT TO Y, ARE                                                  CRAN0400
C                   FOR ABSOLUTE,  0.GE.HBAR.GE.(-2.4809)                CRAN0410
C                   FOR RELATIVE,  INFINITY.GE.HBAR.GE.(-.446)           CRAN0420
C        THE STARTING PROCEDURE IS THE RUNGE-KUTTA VARIANT PUBLISHED BY CRAN0430
C     S. GILL, CAMB. PHIL. SOC. PROC., 47, P96,(1951)                    CRAN0440
C                                                                        CRAN0450
C         TO USE THIS ROUTINE, A SUBROUTINE CALLED DERIV MUST BE PROVI-CRAN0460
C     DED WHICH USES LABELED COMMON/CRANEC/AND CALCULATES THE F VECTOR. CRAN0470
C     THE FIRST CALL OF CRANE WILL ONLY OBTAIN F S,AND SET INIT=1. EACH CRAN0480
C     SUBSEQUENT CALL WILL ADVANCE ONE STEP AND UPDATE X,Y AND F, EXCEPTCRAN0490
C     THAT AFTER THREE STEPS, CRANE MAY HALVE H AND RETURN TO INITIAL   CRAN0500
C     CONDITIONS WITH INIT=4.  (THIS BEHAVIOR WILL RECUR UNTIL PRECISIONCRAN0510
C     IS SATISFIED ACCORDING TO AN ERROR ESTIMATE AFTER THREE STEPS.)   CRAN0520
C                                                                       CRAN0530
C         PRIOR TO FIRST CALL, SET INIT X AND Y AND DEFINE THE VALUES  CRAN0540
C     OF THE NB VECTOR, ALSO DEFINE VALUES OF N,MIN,INIT(=0),IDONT, AND CRAN0550
C     PREC.  PREC SHOULD ADVISEDLY BE FROM 2.5 TO 7. (NOT NECESSARILY   CRAN0560
C     AN INTEGER), THOUGH THERE WILL BE NO EFFECT IF IDONT.NE.0         CRAN0570
C                                                                       CRAN0580
C         PRINTOUT AND TERMINATION ARE NOT ACCOMPLISHED BY CRANE. (NOT)CRAN0590
C                                                                       CRAN0600
C         DO NOT CHANGE X,Y,F,N OR H EXTERNALLY UNLESS YOU SET INIT=0, CRAN0610
C     EXTERNALLY.  HOWEVER, NB AND PREC MAY BE CHANGED AT ANY TIME. SET-CRAN0620
C     TING INIT.LT.0 WILL RESULT IN INHIBITING INCREASE IN H FOR MIN    CRAN0630
C     STEPS, BUT WILL PERMIT DECREASES IN H.  INIT WILL BE POSITIVE ON  CRAN0640
C     EXITTING CRANE AGAIN.                                             CRAN0650
      DIMENSION Q(40),Y1(40),Y0(40),F0(40),F1(40),F2(40),F3(40),F4(40), CRAN0660
     1F5(40),Y2(40) ,E(10),Y3(40),Y4(40),Y5(40)                         CRAN0670
      EQUIVALENCE( Y5(1),Q(1)),(R,T)                                    CRAN0680
C       Y5 AND Q ARE NOT BOTH NEEDED AT THE SAME INSTANT.               CRAN0690
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      DATA KTRU/0/                                                      CRAN0700
C     FIRST EXECUTABLE NEXT                                             CRAN0710
      IF(INIT)1,2,3                                                     CRAN0720
    1 INIT=0                                                            CRAN0730
      E(MIN)=10.                                                        CRAN0740
      IF(KTRU)16,2,16                                                   CRAN0750
    2 IF(N)199,199,555                                                  CRAN0760
  555 IF(N-40)5,5,199                                                   CRAN0770
  199 WRITE(6,200)                                                      CRAN0780
  200 FORMAT(54H0N WAS NOT A POSITIVE INTEGER.LT.40, ON CALLING CRANE.) CRAN0790
      CALL EXIT                                                         CRAN0800
    5 IF(MIN-10)6,7,8                                                   CRAN0810
    8 MIN=10                                                            CRAN0820
    6 IF(MIN-3)9,7,7                                                    CRAN0830
    9 MIN=3                                                             CRAN0840
    7 KTRU=0                                                            CRAN0850
   70 IF(PREC-7.)11,13,12                                               CRAN0860
   12 PREC=7.                                                           CRAN0870
   11 IF(PREC-2.0)14,13,13                                              CRAN0880
   14 PREC=4.                                                           CRAN0890
C      STATEMENT 14 ASSUMES THAT THE OVERSIGHT OF SPECIFYING NO PRECI-  CRAN0900
C     SION, OR PRECISION BELOW 2.0 DECIMALS, SHOULD CALL FOR 4 DECIMALS,CRAN0910
C     VIA INTERNAL CORRECTION.  ALSO, PREC ABOVE 7. IS REDUCED TO 7.    CRAN0920
   13 PRECN=PREC                                                        CRAN0930
      T=10.**(-PREC)                                                    CRAN0940
      BOUNDR=T*16.21966                                                 CRAN0950
      BOUNDA=T*.05                                                      CRAN0960
      BOUND=BOUNDA*FLOAT(MIN)                                           CRAN0970
      IF(INIT)1155,1155,16                                              CRAN0980
 1155 CALL DERIV                                                        CRAN0990
   17 K=0                                                               CRAN1000
      ASSIGN 55 TO IS                                                   CRAN1010
      H1=.5*H                                                           CRAN1020
      KBC=3                                                             CRAN1030
      IF(KTRU  )18,18,20                                                CRAN1040
   15 CALL DERIV                                                        CRAN1050
   18 INIT=1+INIT                                                       CRAN1060
   19 RETURN                                                            CRAN1070
C      THE ABOVE IS THE ONLY RETURN FROM INTODE.  NEXT IS REACHED WHEN  CRAN1080
C     INIT EXCEEDS 0.                                                   CRAN1090
    3 IF(PREC-PRECN)70,16,70                                            CRAN1100
   16 IF (K)20,20,21                                                    CRAN1110
   20 K=4                                                               CRAN1120
  213 DO 22 I=1,N                                                       CRAN1130
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      F3(I)=F2(I)                                                       CRAN1140
      F2(I)=F1(I)                                                       CRAN1150
      F1(I)=F0(I)                                                       CRAN1160
      F0(I)=F(I)                                                        CRAN1170
      Y3(I)=Y2(I)                                                       CRAN1180
      Y2(I)=Y1(I)                                                       CRAN1190
      Y1(I)=Y0(I)                                                       CRAN1200
   22 Y0(I)=Y (I)                                                       CRAN1210
      IF(KBC)23,23,24                                                   CRAN1220
   24 KBC=KBC-1                                                         CRAN1230
      XN=X+H                                                            CRAN1240
      X=X+H1                                                            CRAN1250
      RX=.292893219                                                     CRAN1260
      ASSIGN 33 TO KS                                                   CRAN1270
   37 DO 29 I=1,N                                                       CRAN1280
      AK=H*F(I)                                                         CRAN1290
      GO TO KS,(33,34,30)                                               CRAN1300
   33 Y(I)=Y(I)+0.5*AK                                                  CRAN1310
      Q(I)=AK                                                           CRAN1320
      GO TO 29                                                          CRAN1330
   30 Y(I)=(-Q(I)-Q(I)+AK)*.166666667+Y(I)                              CRAN1340
      GO TO 29                                                          CRAN1350
   34 R=RX*(AK-Q(I))                                                    CRAN1360
      Q(I)=((R+R+R)-RX*AK)+Q(I)                                         CRAN1370
      Y(I)=Y(I)+R                                                       CRAN1380
   29 CONTINUE                                                          CRAN1390
      GO TO (1551, 224, 219, 251),K                                     CRAN1400
  219 RX=1.70710678                                                     CRAN1410
      GO TO 1551                                                        CRAN1420
  251 ASSIGN 34 TO KS                                                   CRAN1430
      GO TO 1551                                                        CRAN1440
  224 ASSIGN 30 TO KS                                                   CRAN1450
      X=XN                                                              CRAN1460
 1551 CALL DERIV                                                        CRAN1470
   36 K=K-1                                                             CRAN1480
      IF(K)18,18,37                                                     CRAN1490
C     THE LOOP BEGINNING AT   37  IS EXCTD 4 TIMES BEFORE ONE STEP IN   CRAN1500
C     DELTAX IS DONE.  THE CODING IS A BIT COMPLEX IN ORDER TO MINIMIZE CRAN1510
C     MULTIPLICATIONS AND INDEXING.  IT IS EQUIVALENT TO SLOWER CODE,   CRAN1520
C     AS FOLLOWS... DO 36 J=1,4    WHEREIN J=5-K                        CRAN1530
C                       DO 29 I=1,N+1                                   CRAN1540
C                       AK(I,J)=DELTAX*F(I)                             CRAN1550
C                       R (I,J)=A(J)*AK(I,J)-B(J)*Q(I)                  CRAN1560
C                       Y (I)  =Y(I)+R(I,J)                             CRAN1570
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C                  Q (I)  =Q(I)+3.* R(I,J)-C(J)*AK(I,J)                 CRAN1580
C               29 X= Y(N+1)                                            CRAN1590
C                  CALL DERIV (X,Y,F)                                   CRAN1600
C               36 CONTINUE                                             CRAN1610
C                  RETURN                                               CRAN1620
C        ACC. TO S. GILL, CAMB. PHIL. SOC., PROC., 47,P96 (1951), THE   CRAN1630
C     VALUES OF A, B , AND C ARE BEST....                               CRAN1640
C            A(J)=0.5,1.-SQRTF(.5),1.+SQRTF(.5),1./6.     J=1,4         CRAN1650
C            B(J)=1. ,1.-SQRTF(.5),1.+SQRTF(.5),1./3.     J=1,4         CRAN1660
C            C(J)=0.5,1.-SQRTF(.5),1.+SQRTF(.5),0.5       J=1,4         CRAN1670
C                                                                       CRAN1680
C     FOLLOWING IS REACHED FROM STMT 16 WHEN KBC=0, AFTER PRED-CORR     CRAN1690
C     INITIALIZATION IS COMPLETE.                                       CRAN1700
   21 IF(IDONT)211,212,211                                              CRAN1710
  211 KBC=0                                                             CRAN1720
      GO TO 213                                                         CRAN1730
  212 IF(E(MIN)-BOUNDA)100,100,28                                       CRAN1740
  100 DO 4 I=2,MIN                                                      CRAN1750
    4 E(1)=E(1)+E(I)                                                    CRAN1760
      IF(E(1)-BOUND)38,28,28                                            CRAN1770
C      28 IS USUAL. 38 IS PREPARE TO DOUBLE DELTAX.                     CRAN1780
   28 DO 39 I=1,N                                                       CRAN1790
      F5(I)=F4(I)                                                       CRAN1800
      F4(I)=F3(I)                                                       CRAN1810
      F3(I)=F2(I)                                                       CRAN1820
      F2(I)=F1(I)                                                       CRAN1830
      F1(I)=F0(I)                                                       CRAN1840
      F0(I)=F (I)                                                       CRAN1850
      Y5(I)=Y4(I)                                                       CRAN1860
      Y4(I)=Y3(I)                                                       CRAN1870
      Y3(I)=Y2(I)                                                       CRAN1880
      Y2(I)=Y1(I)                                                       CRAN1890
      Y1(I)=Y0(I)                                                       CRAN1900
      Y0(I)=Y (I)                                                       CRAN1910
   39 Y(I)=1.547652*Y(I)+2.017204*Y2(I)-1.867503*Y1(I)-.697353*Y3(I)+S* CRAN1920
     1(.965508124*F(I)+.895121303*F2(I)-.351589071*F3(I)-F1(I))         CRAN1930
   40 X=X+H                                                             CRAN1940
      CALL DERIV                                                        CRAN1950
   42 DO 10 I=2,MIN                                                     CRAN1960
   10 E(I-1)=E(I)                                                       CRAN1970
      E(MIN)=0.                                                         CRAN1980
      DO 43 I=1,N                                                       CRAN1990
      T=Y0(I)+AK*(9.*F(I)+19.*F0(I)+F2(I)-5.*F1(I))                     CRAN2000
      PMC=Y(I)-T                                                        CRAN2010
```

```
C        AT THIS POINT, PMC IS PREDICTOR-CORRECTOR                      CRAN2020
      IF(IDONT)43,72,43                                                  CRAN2030
   72 IF(NB(I))43,44,47                                                  CRAN2040
   44 IF (Y(I))46,43,46                                                  CRAN2050
   46 PMC=PMC/Y(I)                                                       CRAN2060
   47 IF(ABS(PMC)-E(MIN))43,43,48                                        CRAN2070
   48 E(MIN)=ABS(PMC)                                                    CRAN2080
   43 Y(I)=T                                                             CRAN2090
C        HERE, E(MIN) IS THE MAX. TRUNC. ERROR EST., ABS. OR REL., OVER ICRAN2100
C     WHILE THIS REST OF E ARE ITS PREDECESSORS.                         CRAN2110
      IF(E(MIN)-BOUNDB)50,50,51                                          CRAN2120
   50 GO TO IS,(15,55)                                                   CRAN2130
C       15 IS NORMAL AND CALLS DERIV, JUMPING TO 18 TO STEP INIT+1,RETURNCRAN2140
C       55 IS REACHED FIRST STEP AFTER A SEQUENCE OF RKG STEPS.(CRD 0510)CRAN2150
C       WHEN LARGEST ERROR EXCEEDS BOUND, STMT 51 IS A BRANCH GOVERNED   CRAN2160
C     BY WHETHER THIS IS ON FIRST P-C STEP OR NOT. 52 IS NORMAL.         CRAN2170
   51 IF(KBC )59,59,52                                                   CRAN2180
C       52 IS REACHED WHEN LARGEST ERROR EXCEEDS BOUND, FNCTN OF PRECISN.CRAN2190
   52 X=X-H                                                              CRAN2200
      DO 54 I=1,N                                                        CRAN2210
      Y(I)=Y0(I)                                                         CRAN2220
   54 F(I)=F0(I)                                                         CRAN2230
   53 H=.625*H                                                           CRAN2240
      GO TO 17                                                           CRAN2250
C       RETURN TO 17 SETS UP RKG INITIALIZATION                          CRAN2260
   55 KBC=3                                                              CRAN2270
      ASSIGN 15 TO IS                                                    CRAN2280
      KTRU=1                                                             CRAN2290
      GO TO 15                                                           CRAN2300
C     ABOVE SEQUENCE COMPLETES INITIALIZATION OF PRED-CORR ROUTINE.      CRAN2310
C       NEXT,FAILURE OF FIRST TEST AFTER RKG SEQUENCE CAUSES BACKUP 3    CRAN2320
C     STEPS.                                                             CRAN2330
   59 X=X-4.*H                                                           CRAN2340
      DO 60 I=1,N                                                        CRAN2350
      Y(I)=Y3(I)                                                         CRAN2360
   60 F(I)=F3(I)                                                         CRAN2370
      GO TO 53                                                           CRAN2380
C       REFER TO CARD 1130 FOR RETURN TO RKG INITIALIZATION.             CRAN2390
C     THE FOLLOWING SETS UP DOUBLING DELTX                               CRAN2400
   58 H=2.*H                                                             CRAN2410
      DO 64 I=1,N                                                        CRAN2420
      F2(I)=F3(I)                                                        CRAN2430
      F3(I)=F5(I)                                                        CRAN2440
      F0(I)=F (I)                                                        CRAN2450
```

```
      Y2(I)=Y3(I)                                                       CRAN2460
      Y3(I)=Y5(I)                                                       CRAN2470
   64 Y0(I)=Y(I)                                                        CRAN2480
C        23 IS REACHED AFTER 3 RKG STEPS, I E WHEN KBC=0.(REF. STTMT 22) CRAN2490
   23 AK=.0416666667*H                                                  CRAN2500
      E(MIN)=10.                                                        CRAN2510
      S=H*2.03169                                                       CRAN2520
      DO 62 I=1,N                                                       CRAN2530
   62 Y(I)=1.547652*Y(I)+2.017204*Y2(I)-1.867503*Y1(I)-.697353*Y3(I)+S* CRAN2540
     1(.965508124*F(I)+.895121303*F2(I)-.351589071*F3(I)-F1(I))         CRAN2550
      GO TO 40                                                          CRAN2560
C       ABOVE CALLS DERIVATIVE WITH FIRST PREDICTED Y VECTOR.           CRAN2570
      END                                                               CRAN2580
```

```
@ FOR DISCOT                                                            DISC0000
      SUBROUTINE DISCOT (XA,ZA,TABX,TABY,TABZ,NC,NY,NZ,ANS)             DISC0010
      DIMENSION TABX(500),TABY(500),TABZ(500),NPX(8),NPY(8),YY(8)       DISC0020
C     DIMENSION TABX(500),TABY(500),TABZ(500),NPX(8),NPY(8),YY(8)       DISC0030
      CALL UNS (NC,IA,IDX,IDZ,IMS)                                      DISC0040
      IF (NZ-1)    5,5,10                                               DISC0050
    5 CALL DISSER (XA,TABX(1),1,NY,IDX,NN)                              DISC0060
      NNN=IDX+1                                                         DISC0070
      CALL LAGRAN (XA,TABX(NN),TABY(NN),NNN,ANS)                        DISC0080
      GOTO 70                                                           DISC0090
   10 ZARG=ZA                                                           DISC0100
      IP1X=IDX+1                                                        DISC0110
      IP1Z=IDZ+1                                                        DISC0120
      IF (IA)    15,25,15                                               DISC0130
   15 IF (ZARG-TABZ(NZ))    25,25,20                                    DISC0140
   20 ZARG=TABZ(NZ)                                                     DISC0150
   25 CALL DISSER (ZARG,TABZ(1),1,NZ,IDZ,NPZ)                           DISC0160
      NX=NY/NZ                                                          DISC0170
      NPZL=NPZ+IDZ                                                      DISC0180
      I=1                                                               DISC0190
      IF (IMS)    30,30,40                                              DISC0200
   30 CALL DISSER (XA,TABX(1),1,NY,IDX,NPX(1))                          DISC0210
      DO 35 JJ=NPZ,NPZL                                                 DISC0220
      NPY(I)=(JJ-1)*NX+NPX(1)                                           DISC0230
      NPX(I)=NPX(1)                                                     DISC0240
   35 I=I+1                                                             DISC0250
      GOTO 50                                                           DISC0260
```

```
40 DO 45 JJ=NPZ,NPZL                                             DISC0270
      IS=(JJ-1)*NX+1                                              DISC0280
      CALL DISSER (XA,TABX(1),IS,NX,IDX,NPX(I))                   DISC0290
      NPY(I)=NPX(I)                                               DISC0300
   45 I=I+1                                                       DISC0310
   50 DO 55 I=1,IP1Z                                              DISC0320
      NLOC=NPX(I)                                                 DISC0330
      NLOCY=NPY(I)                                                DISC0340
   55 CALL LAGRAN (XA,TABX(NLOC),TABY(NLOCY),IP1X,YY(I))          DISC0350
      CALL LAGRAN (ZARG,TABZ(NPZ),YY(1),IP1Z,ANS)                 DISC0360
   70 RETURN                                                      DISC0370
      END                                                         DISC0380
```

```
@ FOR DISSER                                                      DISS0000
      SUBROUTINE DISSER (XA,TAB,I,NX,ID,NPX)                      DISS0010
      DIMENSION TAB(2000)                                         DISS0020
C     DIMENSION TAB(2000)                                         DISS0030
      NPT=ID+1                                                    DISS0040
      NPB=NPT/2                                                   DISS0050
      NPU=NPT-NPB                                                 DISS0060
      IF (NX-NPT)    10,5,10                                      DISS0070
    5 NPX=I                                                       DISS0080
      RETURN                                                      DISS0090
   10 NLOW=I+NPB                                                  DISS0100
      NUPP=I+NX-(NPU+1)                                           DISS0110
      DO 15 II=NLOW,NUPP                                          DISS0120
      NLOC=II                                                     DISS0130
      IF (TAB(II)-XA)    15,20,20                                 DISS0140
   15 CONTINUE                                                    DISS0150
      NPX=NUPP-NPB+1                                              DISS0160
      RETURN                                                      DISS0170
   20 NL=NLOC-NPB                                                 DISS0180
      NU=NL+ID                                                    DISS0190
      DO 25 JJ=NL,NU                                              DISS0200
      NDIS=JJ                                                     DISS0210
      IF (TAB(JJ)-TAB(JJ+1))    25,30,25                          DISS0220
   25 CONTINUE                                                    DISS0230
      NPX=NL                                                      DISS0240
      RETURN                                                      DISS0250
   30 IF (TAB(NDIS)-XA)    40,35,35                               DISS0260
   35 NPX=NDIS-ID                                                 DISS0270
```

```
      RETURN                                                   DISS0280
   40 NPX=NDIS+1                                               DISS0290
      RETURN                                                   DISS0300
      END                                                      DISS0310

@ FOR UNS                                                      UNS 0000
      SUBROUTINE UNS (IC,IA,IDX,IDZ,IMS)                       UNS 0010
      IF (IC)   5,5,10                                         UNS 0020
    5 IMS=1                                                    UNS 0030
      NC=-IC                                                   UNS 0040
      GOTO 15                                                  UNS 0050
   10 IMS=0                                                    UNS 0060
      NC=IC                                                    UNS 0070
   15 IF (NC-100)   20,25,25                                   UNS 0080
   20 IA=0                                                     UNS 0090
      GOTO 30                                                  UNS 0100
   25 IA=1                                                     UNS 0110
      NC=NC-100                                                UNS 0120
   30 IDX=NC/10                                                UNS 0130
      IDZ=NC-IDX*10                                            UNS 0140
      RETURN                                                   UNS 0150
      END                                                      UNS 0160

@ FOR LAGRAN                                                   LAGR0000
      SUBROUTINE LAGRAN (XA,X,Y,N,ANS)                         LAGR0010
      DIMENSION X(200),Y(200)                                  LAGR0020
C     DIMENSION X(200),Y(200)                                  LAGR0030
      SUM=0.0                                                  LAGR0040
      DO 3 I=1,N                                               LAGR0050
      PROD=Y(I)                                                LAGR0060
      DO 2 J=1,N                                               LAGR0070
      A=X(I)-X(J)                                              LAGR0080
      IF (A)   1,2,1                                           LAGR0090
    1 B=(XA-X(J))/A                                            LAGR0100
      PROD=PROD*B                                              LAGR0110
    2 CONTINUE                                                 LAGR0120
    3 SUM=SUM+PROD                                             LAGR0130
      ANS=SUM                                                  LAGR0140
      RETURN                                                   LAGR0150
      END                                                      LAGR0160
```

APPENDIX C

INPUT AND PRINTOUT FOR

SAMPLE PROBLEM

# INPUT FOR SAMPLE PROBLEM

## CARD 1

Title of problem

```
TWO DIMENSIONAL SURFACE FLAW.  SPECIMEN NO. 9L  (2219-T87 ALUMINUM)
```

## CARD 2

Type of flaw: 1.0 = one-dimensional; 2.0 = two-dimensional

```
  2.0
```

## CARD 3

| | |
|---|---|
| Initial crack depth | AI = 0.0660 |
| Plate thickness | T = 0.1259 |
| Initial crack half-width | B = 0.1240 |

```
  0.066     0.1259     0.1240
```

## CARD 4

| | |
|---|---|
| Fracture toughness | KC = 40000.0 |
| Material yield stress | Y = 55500.0 |
| Exponent of DK | S = 2.5 |
| Correction factor | G = 1.12 |
| Material constant for A | CA = $0.14 \times 10^{-10}$ |
| Material constant for B | CB = $0.28 \times 10^{-10}$ |

```
 40000.    55500.      2.5      1.12      0.14 -10  0.28 -10
```

## CARD 5

| | |
|---|---|
| Initial cycle number | NI = 0.0 |
| Cycle print interval | DN = 10.0 |
| Start cycle print | START = 40000.0 |
| Number load conditions | NL = 1 |
| Number load blocks | NBLK = 1 |

```
  0.0       10.0      40000.            1           1
```

C FOR COMMENT | STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION

## CARD 6

| | |
|---|---|
| Number of Q values | IQ = 21 |
| Flag for reading Q table | MQTBL = 1 |
| Number of F values | IF = 12 |
| Flag for reading F table | MFTBL = 1 |

```
       21          1           12          1
```

C FOR COMMENT | STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION

## CARD 7 (21 cards) (only the first card is shown.)

21 values of A/B compared with $\Phi^2$ from table IV.

```
 0.0          1.0
```

C FOR COMMENT | STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION

## CARD 8 (12 cards) (only the first card is shown.)

12 values of A/B compared with F from table I.

```
  0.0         1.120
```

C FOR COMMENT | STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION

**CARD 9** (1 card since there is one load condition)

| | |
|---|---|
| Final cycle number | NF = 40000.0 |
| Cyclic stress range | DP = 19570.0 |
| Cyclic stress ratio | R = 0.01 |
| Step size | HH = 10.0 |
| Precision | PRC = 7.0 |
| Step change | ISC = 0 |

```
40000.   19570.     0.01      1.0        7.0            0
```

NOTE: For the second specimen, the only changes made to the above cards are shown below. The method of input for the additional specimens is identical.

**CARD 1**

```
TWO DIMENSIONAL SURFACE FLAW.  SPECIMEN NO. 10L  (2219-T87 ALUMINUM)
```

**CARD 3**

```
0.067    0.1245     0.1265
```

**CARD 6**

```
  21                       12
```

**CARD 7**

These cards are not entered for this problem because they were read in for the first problem.

## CARD 8

These cards were not entered for this problem because they were read in for the first problem.

## CARD 9

```
40000.    27690.    0.01    1.0    7.0
```

# PRINTOUT FOR SAMPLE PROBLEM

TWO DIMENSIONAL SURFACE FLAW. SPECIMEN NO. 9L (2219-T87 ALUMINUM)

CRACK PROPAGATION STUDY

INPUT

| | | |
|---|---|---|
| INITIAL CRACK DEPTH | AI = | .66000000-01 |
| PLATE THICKNESS | T = | .12590000+00 |
| INITIAL CRACK WIDTH | B = | .12400000+00 |
| FRACTURE TOUGHNESS | KC = | .40000000+05 |
| MATERIAL YIELD STRESS | Y = | .55500000+05 |
| EXPONENT OF DK | S = | .25000000+01 |
| CORRECTION FACTOR | G = | .11200000+01 |
| MATERIAL CONSTANT FOR A | CA = | .14000000-10 |
| MATERIAL CONSTANT FOR B | CB = | .28000000-10 |
| INITIAL CYCLE NUMBER | NI = | .00000000 |
| CYCLE PRINT INTERVAL | DN = | .10000000+02 |
| NUMBER LOAD CONDITIONS | NL = | 1 |
| NUMBER LOAD BLOCKS | LDS= | 1 |
| NUMBER OF Q VALUES | IQ = | 21 |
| NUMBER OF F VALUES | IF = | 12 |

| A/B OR B/A | PHI(SQUARED) |
|---|---|
| .00000000 | .10000000+01 |
| .22361000+00 | .11246050+01 |
| .31622000+00 | .12205270+01 |
| .38729000+00 | .13073540+01 |
| .44721000+00 | .13888380+01 |
| .50000000+00 | .14666560+01 |
| .54772000+00 | .15417460+01 |
| .59161000+00 | .16147720+01 |
| .63245000+00 | .16859150+01 |
| .67082000+00 | .17556880+01 |
| .70710000+00 | .18242390+01 |

| | |
|---|---|
| .74162000+00 | .18917300+01 |
| .77459000+00 | .19582970+01 |
| .80622000+00 | .20240490+01 |
| .83666000+00 | .20890740+01 |
| .86602000+00 | .21534440+01 |
| .89443000+00 | .22172250+01 |
| .92195000+00 | .22804680+01 |
| .94868000+00 | .23432200+01 |
| .97468000+00 | .24055170+01 |
| .10000000+01 | .24674000+01 |

| A/B | F |
|---|---|
| .00000000 | .11200000+01 |
| .10000000+00 | .11080000+01 |
| .20000000+00 | .10970000+01 |
| .30000000+00 | .10870000+01 |
| .40000000+00 | .10770000+01 |
| .50000000+00 | .10670000+01 |
| .60000000+00 | .10590000+01 |
| .70000000+00 | .10510000+01 |
| .80000000+00 | .10430000+01 |
| .90000000+00 | .10360000+01 |
| .10000000+01 | .10300000+01 |
| .20000000+01 | .10000000+01 |

OUTPUT

BLOCK LOAD NO. 1

| | | |
|---|---|---|
| FINAL CYCLE NUMBER | NF = | .40000000+05 |
| CYCLIC STRESS RANGE | DP = | .19570000+05 |
| CYCLIC STRESS RATIO | R = | .10000000-01 |
| STEP SIZE | H = | .10000000+01 |
| PRECISION | PRC= | .70000000+01 |
| STEP CHANGE | ISC= | 0 |
| START CYCLE PRINT | START= | .40000000+05 |

| N | A | B | DA/DN | DB/DN | DK(A) | DK(B) | Q |
|---|---|---|---|---|---|---|---|
| .00000000 | .66000000-01 | .12400000+00 | .25703528-05 | .22856161-05 | .80390698+04 | .59630026+04 | .14910896+01 |
| .13253000+05 | .12593194+00 | .17348037+00 | .12091028-04 | .63389171-05 | .13781761+05 | .86713588+04 | .18349097+01 |

TWO DIMENSIONAL SURFACE FLAW. SPECIMEN NO. 10L (2219-T87 ALUMINUM)

CRACK PROPAGATION STUDY

INPUT

| | | |
|---|---|---|
| INITIAL CRACK DEPTH | AI = | .67000000-01 |
| PLATE THICKNESS | T = | .12450000+00 |
| INITIAL CRACK WIDTH | B = | .12650000+00 |
| FRACTURE TOUGHNESS | KC = | .40000000+05 |
| MATERIAL YIELD STRESS | Y = | .55500000+05 |
| EXPONENT OF DK | S = | .25000000+01 |
| CORRECTION FACTOR | G = | .11200000+01 |
| MATERIAL CONSTANT FOR A | CA = | .14000000-10 |
| MATERIAL CONSTANT FOR B | CB = | .28000000-10 |
| INITIAL CYCLE NUMBER | NI = | .00000000 |
| CYCLE PRINT INTERVAL | DN = | .10000000+02 |
| NUMBER LOAD CONDITIONS | NL = | 1 |
| NUMBER LOAD BLOCKS | LDS= | 1 |
| NUMBER OF Q VALUES | IQ = | 21 |
| NUMBER OF F VALUES | IF = | 12 |

NOTE-- THE A/B OR B/A VS. PHI(SQUARED) TABLE FOR THIS CASE IS THE SAME AS THE PRECEEDING CASE

NOTE-- THE A/B VS. F TABLE FOR THIS CASE IS THE SAME AS THE PRECEEDING CASE

OUTPUT
BLOCK LOAD NO. 1

| | | |
|---|---|---|
| FINAL CYCLE NUMBER | NF = | .40000000+05 |
| CYCLIC STRESS RANGE | DP = | .27690000+05 |
| CYCLIC STRESS RATIO | R = | .10000000-01 |
| STEP SIZE | H = | .10000000+01 |
| PRECISION | PRC= | .70000000+01 |
| STEP CHANGE | ISC= | 0 |
| START CYCLE PRINT | START= | .40000000+05 |

| N | A | B | DA/DN | DB/DN | DK(A) | DK(B) | Q |
|---|---|---|---|---|---|---|---|
| .00000000 | .67000000-01 | .12650000+00 | .72971719-05 | .61285903-05 | .11627885+05 | .85666760+04 | .14610538+01 |
| .44350000+04 | .12460623+00 | .17080691+00 | .36934469-04 | .17200877-04 | .19492410+05 | .12298008+05 | .18160856+01 |

TWO DIMENSIONAL SURFACE FLAW. SPECIMEN NO. 12M (2219-T87 ALUMINUM)

CRACK PROPAGATION STUDY

INPUT

| | | |
|---|---|---|
| INITIAL CRACK DEPTH | AI = | .65000000-01 |
| PLATE THICKNESS | T = | .12550000+00 |
| INITIAL CRACK WIDTH | B = | .13150000+00 |
| FRACTURE TOUGHNESS | KC = | .40000000+05 |
| MATERIAL YIELD STRESS | Y = | .55500000+05 |
| EXPONENT OF DK | S = | .26000000+01 |
| CORRECTION FACTOR | G = | .11200000+01 |
| MATERIAL CONSTANT FOR A | CA = | .14000000-10 |
| MATERIAL CONSTANT FOR B | CB = | .28000000-10 |
| INITIAL CYCLE NUMBER | NI = | .00000000 |
| CYCLE PRINT INTERVAL | DN = | .10000000+02 |
| NUMBER LOAD CONDITIONS | NL = | 1 |
| NUMBER LOAD BLOCKS | LDS= | 1 |
| NUMBER OF Q VALUES | IQ = | 21 |
| NUMBER OF F VALUES | IF = | 12 |

NOTE-- THE A/B OR B/A VS. PHI(SQUARED) TABLE FOR THIS CASE IS THE SAME AS THE PRECEEDING CASE

NOTE-- THE A/B VS. F TABLE FOR THIS CASE IS THE SAME AS THE PRECEEDING CASE

OUTPUT

BLOCK LOAD NO. 1

| | | |
|---|---|---|
| FINAL CYCLE NUMBER | NF = | .40000000+05 |
| CYCLIC STRESS RANGE | DP = | .31540000+05 |
| CYCLIC STRESS RATIO | R = | .10000000-01 |
| STEP SIZE | H = | .10000000+01 |
| PRECISION | PRC= | .70000000+01 |
| STEP CHANGE | ISC= | 0 |
| START CYCLE PRINT | START= | .40000000+05 |

| N | A | B | DA/DN | DB/DN | DK(A) | DK(B) | Q |
|---|---|---|---|---|---|---|---|
| .00000000 | .65000000-01 | .13150000+00 | .11021573-04 | .82219570-05 | .13365759+05 | .95161298+04 | .13908795+01 |
| .30060000+04 | .12552913+00 | .17423380+00 | .62553058-04 | .25928876-04 | .22536126+05 | .14101255+05 | .17829959+01 |

TWO DIMENSIONAL SURFACE FLAW. SPECIMEN NO. 14M (2219-T87 ALUMINUM)

CRACK PROPAGATION STUDY

INPUT

| | | |
|---|---|---|
| INITIAL CRACK DEPTH | AI = | .63000000-01 |
| PLATE THICKNESS | T = | .11930000+00 |
| INITIAL CRACK WIDTH | B = | .12850000+00 |
| FRACTURE TOUGHNESS | KC = | .40000000+05 |
| MATERIAL YIELD STRESS | Y = | .55500000+05 |
| EXPONENT OF DK | S = | .25000000+01 |
| CORRECTION FACTOR | G = | .11200000+01 |
| MATERIAL CONSTANT FOR A | CA = | .14000000-10 |
| MATERIAL CONSTANT FOR B | CB = | .28000000-10 |
| INITIAL CYCLE NUMBER | NI = | .00000000 |
| CYCLE PRINT INTERVAL | DN = | .10000000+02 |
| NUMBER LOAD CONDITIONS | NL = | 1 |
| NUMBER LOAD BLOCKS | LDS= | 1 |
| NUMBER OF Q VALUES | IQ = | 21 |
| NUMBER OF F VALUES | IF = | 12 |

NOTE-- THE A/B OR B/A VS. PHI(SQUARED) TABLE FOR THIS CASE IS THE SAME AS THE PRECEEDING CASE

NOTE-- THE A/B VS. F TABLE FOR THIS CASE IS THE SAME AS THE PRECEEDING CASE

OUTPUT
BLOCK LOAD NO. 1

| | | |
|---|---|---|
| FINAL CYCLE NUMBER | NF = | .40000000+05 |
| CYCLIC STRESS RANGE | DP = | .41450000+05 |
| CYCLIC STRESS RATIO | R = | .10000000-01 |
| STEP SIZE | H = | .10000000+01 |
| PRECISION | PRC= | .70000000+01 |
| STEP CHANGE | ISC= | 0 |
| START CYCLE PRINT | START= | .40000000+05 |

| N | A | B | DA/DN | DB/DN | DK(A) | DK(B) | Q |
|---|---|---|---|---|---|---|---|
| .00000000 | .63000000-01 | .12850000+00 | .26711218-04 | .18097792-04 | .17713266+05 | .12511296+05 | .13360057+01 |
| .11150000+04 | .11940182+00 | .16363161+00 | .19179340-03 | .60082526-04 | .29076634+05 | .18348228+05 | .17522716+01 |



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