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DEVELOPMENT OF THE NASA/FLAGRO COMPUTER PROGRAM FOR ANALYSIS OF AIRFRAME STRUCTURES

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R. G. Forman
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

V. Shivakumar
Lockheed Engineering and Sciences Co.
2400 NASA Road 1
Houston, Texas 77058

J. C. Newman, Jr.
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

SUMMARY

The NASA/FLAGRO (NASGRO) computer program was developed for fracture control analysis of space hardware and is currently the standard computer code in NASA, the U.S. Air Force, and the European Space Agency (ESA) for this purpose. The significant attributes of the NASGRO program are the numerous crack case solutions, the large materials file, the improved growth rate equation based on crack closure theory, and the user-friendly promptive input features.

In support of the National Aging Aircraft Research Program (NAARP), NASGRO is being further developed to provide advanced state-of-the-art capability for damage tolerance and crack growth analysis of aircraft structural problems, including mechanical systems and engines. The project currently involves a cooperative development effort by NASA ,FAA, and ESA. The primary tasks underway are the incorporation of advanced methodology for crack growth rate retardation resulting from spectrum loading and improved analysis for determining crack instability. Also, the current weight function solutions in NASGRO for nonlinear stress gradient problems are being extended to more crack cases, and the 2-d boundary integral routine for stress analysis and stress-intensity factor solutions is being extended to 3-d problems. Lastly, effort is underway to enhance the program to operate on personal computers and work stations in a Windows environment. Because of the increasing and already wide usage of NASGRO, the code offers an excellent mechanism for technology transfer for new fatigue and fracture mechanics capabilities developed within NAARP.

INTRODUCTION

The NASGRO computer program was developed to provide an automated procedure for fracture control analysis of NASA space flight hardware and launch support facilities. In addition, it is applicable to analysis of non aerospace structures or hardware and may be used as a learning and research tool in fracture mechanics. The primary capability of the program is to calculate fatigue life and crack instability of cyclically or statically loaded structures which contain initial crack-like defects. The original version of NASGRO was completed in August 1986 and was revised in March 1989. General distribution of the program was initiated in 1990 by COSMIC*, the agency that distributes NASA-developed computer software.

Features of NASGRO that are new for the current version 2.0 include:

1) new and improved stress intensity factor solutions
2) an improved fatigue crack growth equation
3) expansion of the material properties file by over 300%
4) provisions for combining different blocks of a fatigue spectrum to form a load schedule
5) capacity for applying partial or fractional load cycles
6) option for plotting a vs. N during safe-life analysis
7) addition of sustained stress (da/dt) life analysis
8) capability for running the program by batch file as well as interactively
9) personal computer (PC) operating capability, including a Macintosh version
10) addition of boundary element method for performing stress analysis and obtaining stress intensity factor solutions
11) usage of weight function methods to analyze several crack cases with nonlinear stresses
12) improved user interface with ability to readily correct input errors

The program has been designed in a modular fashion, in order to allow for systematic revision and portability to various computer systems including main frame, personal computers, and work stations.

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*COSMIC -(706)-542-3265
The University of Georgia
382 East Broad Street
Athens, Georgia 30602

VERSION 2.0 ADVANCED FEATURES

Crack Growth Relationship

Crack growth rate calculations in NASGRO 2.0 use a recently improved relationship* called the NASGRO 2.0 equation which is given by:

$$\frac{da}{dN} = \frac{C(1-f)^n \Delta K^n \left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p}{(1-R)^n \left(1 - \frac{\Delta K}{(1-R)K_c}\right)^q} \tag{1}$$

where N is the number of applied fatigue cycles, a is the crack length, R is the stress ratio, ΔK is the stress intensity factor range, and C, n, p, and q are empirically derived constants. Equation 1 produces da/dN-ΔK curves that are similar to those obtained from the equation used in earlier versions of NASGRO, but it provides a more direct formulation of the stress-ratio effect. Also, with Eq 1, variations in K_c and ΔK_{th} values have a reduced effect on the linear region of the curve, which produces a better fit to data. Figure 1 shows crack growth (da/dN-ΔK) data for aluminum-bronze CDA630, plotted together with a curve fit to Eq 1.

To analyze problems with combined loading, the stress intensity factor is expressed as:

$$K = \left[S_0 F_0 + S_1 F_1 + S_2 F_2 + S_3 F_3 + S_4 F_4\right]\sqrt{\pi a} \tag{2}$$

The stress quantities S_0, S_1, S_2, and S_3 are the applied tension/compression, bending in the thickness and width directions, and pin bearing pressures. For the crack cases of biaxial tension/compression loading, the term S_4 is used for the stress in the lateral direction. The F values are geometric correction factors applicable to each type of applied stress and derived specifically for each crack case.

The program incorporates fatigue crack closure analysis for calculating the effect of the stress ratio on crack growth rate under constant amplitude loading. The crack opening function *f*, for plasticity-induced crack closure has been defined by Newman (ref. 1) as:

$$f = \frac{K_{op}}{K_{max}} = \begin{cases} \max\left(R, A_0 + A_1 R + A_2 R^2 + A_3 R^3\right) & R \geq 0 \\ A_0 + A_1 R & -2 \leq R < 0 \end{cases} \tag{3}$$

* Formulated for NASGRO 2.0 where different elements of the equation were obtained by Forman and Newman at NASA, de Koning at NLR, and Henriksen at ESA.

and the coefficients are given by:

$$A_0 = \left(0.825 - 0.34\alpha + 0.05\alpha^2\right)\left[\cos\left(\frac{\pi}{2}S_{max}/\sigma_0\right)\right]^{1/\alpha} \quad (4)$$

$$A_1 = (0.415 - 0.071\alpha)S_{max}/\sigma_0 \quad (5)$$

$$A_2 = 1 - A_0 - A_1 - A_3 \quad (6)$$

$$A_3 = 2A_0 + A_1 - 1 \quad (7)$$

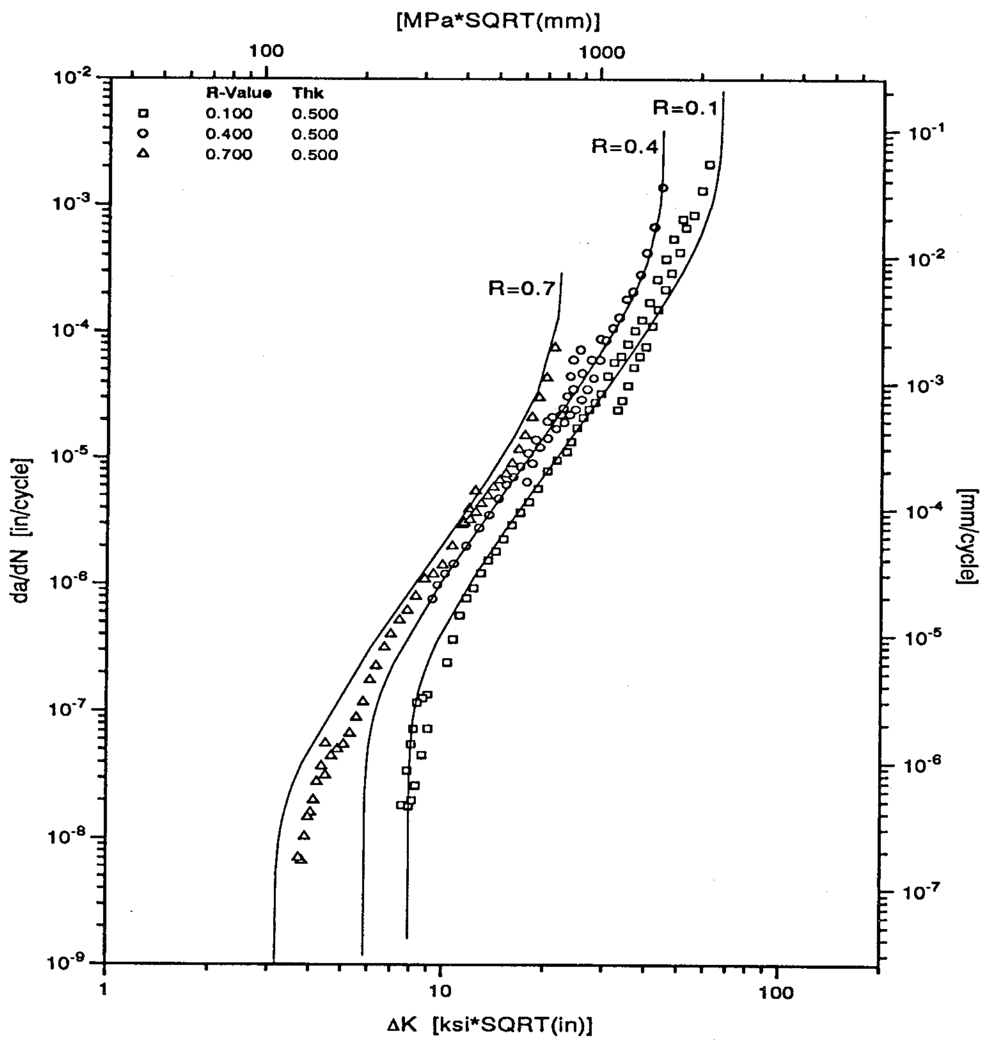


Figure 1 - Curve fit to Eq. 1 for aluminum-bronze CDA630

In these equations, α is a plane stress/strain constraint factor, and S_{max}/σ_0 is the ratio of the maximum applied stress to the flow stress.

It should be noted that Eq. 1 may be reduced to the Paris equation with closure by setting p=q=0. The Paris equation with no closure can be further obtained by making f=R which is the case when $S_{max}/\sigma_0 = 1.0$ and $\alpha = 5.845$.

Threshold Stress Intensity Factor Range

The threshold stress intensity factor range in Eq 1, ΔK_{th}, is approximated as a function of the stress ratio, R, the threshold stress intensity factor range at R = 0, ΔK_0, the crack length, a, and an intrinsic crack length a_0, by the following empirical equation:

$$\Delta K_{th} = \Delta K_0 \left[\frac{4}{\pi} \tan^{-1}(1-R) \right] \left(\frac{a}{a + a_0} \right)^{1/2} \qquad (8)$$

This is a modification of a previous arctan rule (ref. 2) that takes into consideration the small crack effect demonstrated by Tanaka, et al. (ref. 3). The arctan form of the equation was chosen over the ΔK_{th} formulation included in the previous NASGRO version because it provides for a reduced nonlinear threshold behavior at negative stress ratios. Values of ΔK_0 are stored as constants in the NASGRO materials files, and a_0 has been assigned a fixed value of 0.004 in. (0.102 mm). This value agrees with an onset of short crack behavior at 0.025 in. (0.635 mm) which was coded into the previous NASGRO version and also agrees with the decrease in threshold with crack size shown by Tanaka for numerous steel alloys.

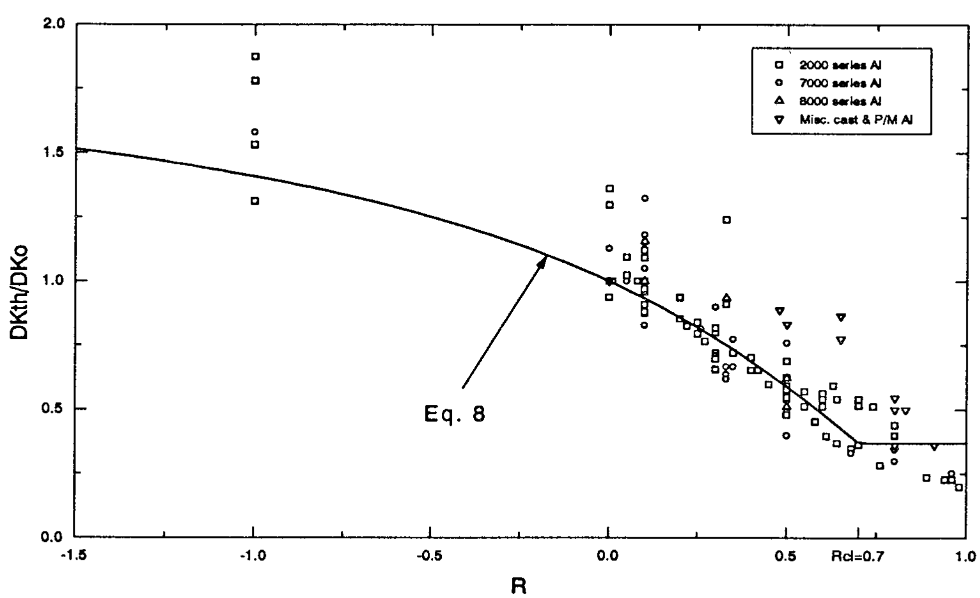


Figure 2 Crack growth threshold vs. R for aluminum

A comparison of ΔK_{th} vs. R data for several aluminum alloys with a curve fit according to Eq 8 indicates good agreement in Figure 2. As seen in this figure, ΔK_{th} approaches a constant value with increasing stress ratio. This effect is consistent with the decrease in crack closure observed at higher stress ratios, and thus R_{cl} has been defined as the stress ratio above which ΔK_{th} no longer changes (ref. 4). In most alloys, R_{cl} was determined to be about 0.7, so this value was used for materials when data at higher stress ratios were not available.

Stress Intensity Factor Solutions Using Weight Function Method

The weight function method was conceived by Bueckner (ref. 5) and Rice (ref. 6) and was used by several investigators to generalize the stress intensity factor solutions for cracks subjected to arbitrary loading. For one-dimensional variation of stresses acting across the potential crack plane, the basic relation between the stress intensity factor and the stress distribution is given by

$$K_r = \int_0^a \sigma_r(x) m(x,a)\, dx \tag{9}$$

where $\sigma_r(x)$ is the stress distribution on the crack face and *m(x,a)* is the weight function which varies with the position coordinate x and the crack length a. Once the weight function is known, the stress intensity factor can be obtained by numerical quadrature. Variations in implementing the weight function scheme are essentially in the way the function *m(x,a)* is obtained. It can be shown that

$$m(x,a) = \frac{H}{K}\frac{\delta u(x,a)}{\delta a} \tag{10}$$

where the stress intensity factor K and the crack face displacement *u(x,a)* correspond to the same applied loading. H is a material constant and a is the crack length.

A new approach to computing the weight function was proposed by Shen and Glinka (ref.7, ref.8). In their approach, the weight function is assumed to be a four-term approximation in the form

$$m(x,a) = \frac{2}{\sqrt{2\pi(a-x)}}\left(1 + M_1\left(1-\frac{x}{a}\right)^{1/2} + M_2\left(1-\frac{x}{a}\right) + M_3\left(1-\frac{x}{a}\right)^{3/2}\right) \tag{11}$$

where the crack tip is at $x = a$. In principle, the three constants M_1, M_2, M_3 can be determined from three reference solutions for the stress intensity factors and there would be no need to obtain the displacement field. Thus, the inaccuracies resulting from numerical differentiation of the displacement field are avoided. The novelty of the present method introduced in NASGRO is in going another step forward by direct and accurate usage of numerical reference solutions in tabular form as opposed to using reference solutions in analytical form. Two important surface crack cases where reference solutions have been obtained by accurate finite element analysis, and the weight functions incorporated are shown in Figure 3. References 9 and 10 document the implementation of the weight function method for these two crack cases. In the solutions, the weight functions are given for the surface point or c-tip in our notation by

$$m_B(x,a) = \frac{2}{\sqrt{\pi x}}\left(1 + M_{1B}\left(\frac{x}{a}\right)^{1/2} + M_{2B}\left(\frac{x}{a}\right) + M_{3B}\left(\frac{x}{a}\right)^{3/2}\right) \tag{12}$$

and for the deepest point or a-tip, by

$$m_A(x,a) = \frac{2}{\sqrt{2\pi(a-x)}}\left(1 + M_{1A}\left(1-\frac{x}{a}\right)^{1/2} + M_{2A}\left(1-\frac{x}{a}\right) + M_{3A}\left(1-\frac{x}{a}\right)^{3/2}\right) \tag{13}$$

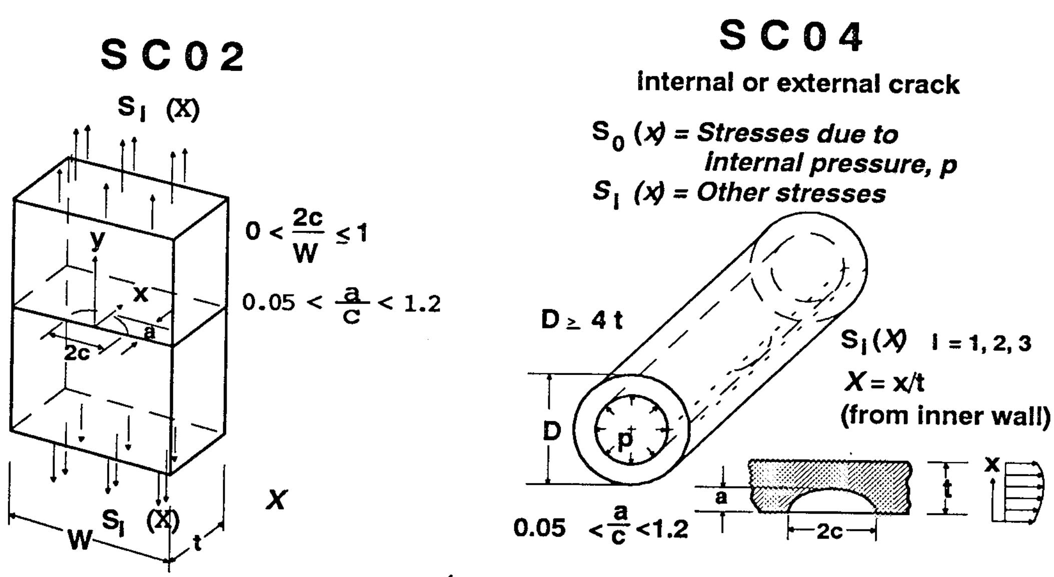
In order to solve for the three constants in each of the above two equations, two reference solutions and a third condition are used. The third condition for the c-tip is that the weight function vanishes at $x = a$ which gives

$$1 + M_{1B} + M_{2B} + M_{3B} = 0 \tag{14}$$

and the third condition for the a-tip is that the second derivative of the weight function be zero at $x = 0$ leading to

$$M_{2A} = 3 \tag{15}$$

For both crack cases, the two reference solutions used are the case of uniform tension and linearly decreasing stress as illustrated in Figure 4.



a. Surface crack in flat plate (SC02) b. Axial surface crack in hollow cylinder (SC04)

Figure 3. Weight function crack case solutions

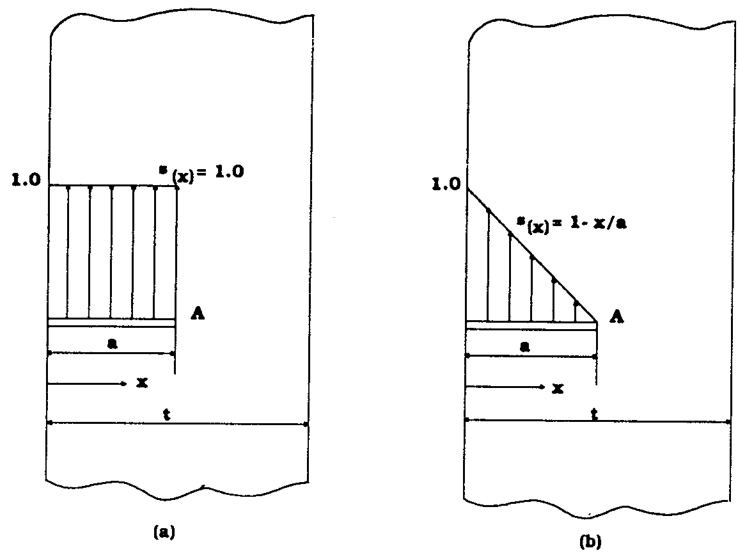


Figure 4 Two reference stresses used in the weight function method

As previously mentioned, more accurate weight function solutions were obtained by direct and accurate usage of numerical solutions in tabular form. Most surface and corner crack solutions in NASGRO 2.0 are in tabular form, both for weight function reference solutions and the other solutions, and were obtained by finite element analysis.

Unique nonlinear interpolation routines were developed for accurate and efficient table look-up of the tabular solutions. Since most tables are multi-dimensional (e.g., variables of a/c, a/t, 2c/w as in SC02 in Figure 3), preprocessing is performed after entry of geometry dimensions to derive a two dimensional table for a specific problem. Spline coefficients are calculated for this reduced table and reordered into a one-dimensional array for use in the crack growth analysis. This special preprocessing and reduction of array dimensions reduces the computer time to approximately a twentieth of that taken by a direct multi-dimensional and nonlinear interpolation procedure.

Boundary Element Method Analysis

The boundary element method (BEM) for solving complex geometry crack problems is particularly advantageous because only the interior and exterior boundaries must be discretized and no interior meshing is required such as for the finite element method. The BEM routine in NASGRO 2.0 is an advanced computational scheme for two-dimensional linear elastic analysis which overcomes the drawbacks of earlier developed BEM techniques. The analytical formulation and computer code for stress-intensity factor computations were developed by C. Chang (ref. 11) under a NASA grant from Langley Research Center. The user interface to the code and the formulation and coding for stress analysis capability were performed by V. Shivakumar and J. Beek, Lockheed Corporation, in support of the NASGRO development task at the Johnson Space Center.

For the crack analysis, the technique developed is essentially a modified boundary element scheme in which ordinary boundaries (i.e., boundaries other than crack surfaces) are modeled by conventional boundary integrals, while crack lines are modeled by integrals representing distributions of point dislocations and point loads. The formulation is similar to that given by Zang and Gudmundson (ref. 10), although the development and implementation differ in several important aspects which lead to a more complete and robust numerical strategy.

The advantage of the dislocation/BEM is that the solutions are highly accurate and efficient and the crack is only modeled by a single line of node points. The crack can be straight, curved, or even kinked. Quadratic type boundary elements are used which increase the accuracy of the results.

A summary of the BEM routine capabilities in NASGRO are as follows:

1. Arbitrary number of boundaries and cracks
2. Traction, displacement, and mixed boundary conditions
3. Internal and surface breaking cracks
4. Multiple material regions (e.g., sub structuring)
5. Simple modeling for multiple crack length solutions

Figure 5 shows the satisfactory accuracy for a very coarse mesh problem compared to a fine mesh modeled problem. The computer run time for the coarse mesh case was approximately 20 seconds for each crack length using an HP9000 work station.

Finally, Figure 6 illustrates the utility in NASGRO of applying the weight function analysis in conjunction with the BEM stress analysis. The problem illustrated is a stepped plate for which a solution is needed for a surface crack at the step radius location. The needed stress solution, $\sigma_z(x)$, on the crack plane without the crack is first calculated with the BEM 2-d routine; then the stress-intensity-factor solution is obtained using the weight function solution for a surface crack in a flat plate as shown earlier in Figure 3.

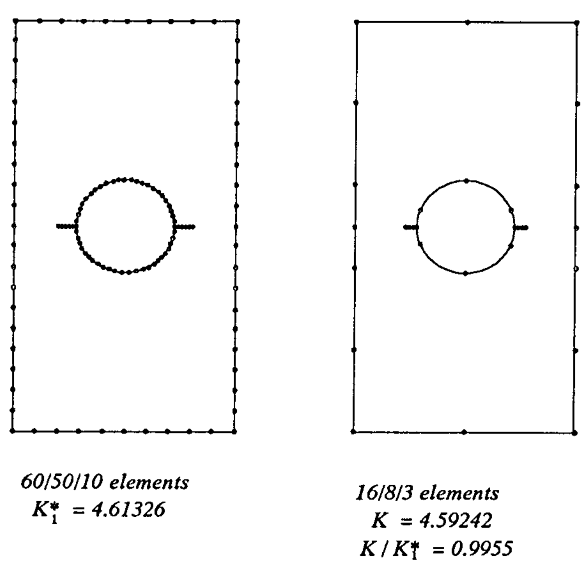
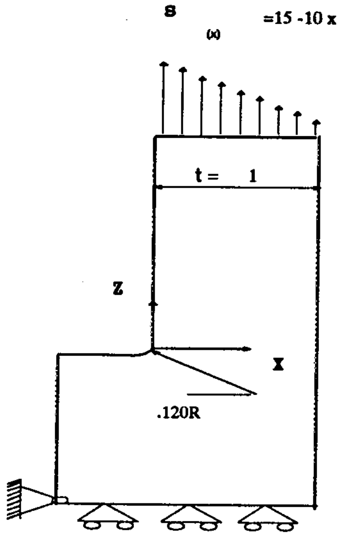
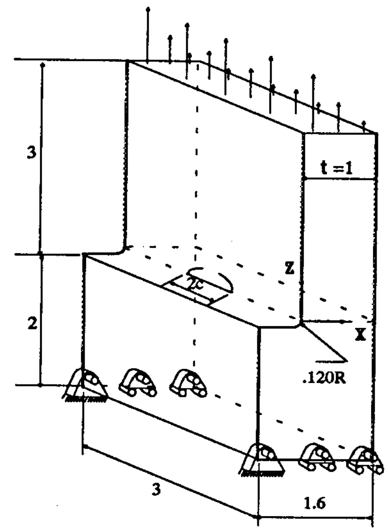


Figure 5 Comparison of fine versus coarse mesh solutions



x/t	s z(ksi)
0.000	24.17
0.005	23.08
0.010	22.04
0.015	21.10
0.020	20.27
0.025	19.53
0.035	18.27
0.045	17.26
0.060	16.08
0.075	15.18
0.095	14.26
0.130	13.14
0.180	12.11
0.250	11.18
0.350	10.28
0.500	9.272
0.700	8.087
0.850	7.122
0.900	6.759
1.000	5.929



2-d BEM Stress Analysis Model

BEM Stress Analysis Results

Wt. Function Model (SC02) for Surface Crack Analysis using 2-d σ_z Results

Figure 6 Application of BEM 2-d stress analysis in conjunction with 3-d weight function solutions

Future NASGRO Enhancements

Further development and improvements to NASGRO are covered by ongoing and scheduled long term task efforts. The future enhanced capabilities will be a function of improvements both in computer technology and in understanding and modeling fatigue crack growth and crack instability behavior.

Since analysis capabilities are strongly driven by computer power and speed, many improved features will be incorporated in NASGRO as computer capabilities increase. This is particularly applicable to 3-d BEM analysis, elastic-plastic analysis, and improved fatigue crack growth analysis which accurately accounts for variable amplitude loading. For instance, the current state-of-the-art in personal computer microprocessors is a speed of approximately 100 million instructions per second (MIPS). The expected capability for microprocessors in four more years is 2000 MIPS, or a 20 fold increase. In addition to this advancement, future development of NASGRO will be combined with improvements in computer operating systems, such as forthcoming advanced Windows type environments that will improve code portability and make NASGRO even more user-friendly.

The improvements in understanding crack growth behavior and development of appropriate modeling will be derived from research and development tasks now underway by NASA and other organizations, and these improvements will feed into future NASGRO versions. Both 3.0 and 4.0 versions are currently scheduled and will consist essentially of the following developments or enhancements:

3.0 VERSION - (1995)

(1) Incorporate de Koning-Newman strip-yield & Willenborg retardation routines

(2) Incorporate environmentally accelerated crack growth analysis capability

(3) Expand weight function K solutions to many more crack cases

(4) Expand materials properties file

4.0 VERSION - (1997):

(1) Incorporate 3-d BEM routine

(2) Enhance retardation & environmental da/dN routines

(3) Crack instability analysis improvement (K-R curve or Newman 2-parameter)

On-Going Development Tasks/Studies

(1) Small crack effects - constant amplitude & spectrum loading

(2) ΔK_{th} behavior & modeling

(3) New/more accurate crack case solutions

(4) Code compatibility with different fatigue spectrum input formats

(5) Compatibility with different computer systems & Windows environments

Conclusions

The NASGRO computer program offers an advanced state-of-the-art software package for aircraft damage tolerance and durability analysis. The code also offers an excellent mechanism for technology transfer for new fatigue and fracture mechanics capabilities developed within NAARP. The current 2.0 version offers numerous improvements over the previous 1989 version, and future improvements are planned for versions 3.0 and 4.0.

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