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NASGRO 3.0 - A SOFTWARE FOR ANALYZING AGING AIRCRAFT

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ABSTRACT

Structural integrity analysis of aging aircraft is a critical necessity in view of the increasing numbers of such aircraft in general aviation, the airlines and the military. Efforts are in progress by NASA, the FAA and the DoD to focus attention on aging aircraft safety. The present paper describes the NASGRO software which is well-suited for effectively analyzing the behavior of defects that may be found in aging aircraft. The newly revised Version 3.0 has many features specifically implemented to suit the needs of the aircraft community. The fatigue crack growth computer program NASA/FLAGRO 2.0 was originally developed to analyze space hardware such as the Space Shuttle, the International Space Station and the associated payloads. Due to popular demand, the software was enhanced to suit the needs of the aircraft industry. Major improvements in Version 3.0 are the incorporation of the ability to read aircraft spectra of unlimited size, generation of common aircraft fatigue load blocks, and the incorporation of crack-growth models which include load-interaction effects such as retardation due to overloads and acceleration due to underloads. Five new crack-growth models, viz., generalized Willenborg, modified generalized Willenborg, constant closure model, Walker-Chang model and the deKoning-Newman strip-yield model, have been implemented. To facilitate easier input of geometry, material properties and load spectra, a Windows-style graphical user interface has been developed. Features to quickly change the input and rerun the problem as well as examine the output are incorporated. NASGRO has been organized into three modules, the crack-growth module being the primary one. The other two modules are the boundary element module and the material properties module. The boundary-element module provides the ability to model and analyze complex two-dimensional problems to obtain stresses and stress-intensity factors. The material properties module allows users to store and curve-fit fatigue-crack growth data. On-line help and documentation are provided for each of the modules. In addition to the popular PC windows version, a unix-based X-windows version of NASGRO is also available. A portable C++ class library called WxWindows was used to facilitate cross-platform availability of the software.

1. INTRODUCTION

Structural integrity analysis of aging aircraft is a critical necessity in view of the increasing numbers of such aircraft in general aviation, the airlines and the military. Damage tolerance analysis can be used to assess the remaining life of aircraft in service. It also provides a basis for setting up proper inspection intervals and a maintenance schedule for aging aircraft. The efforts of NASA, the FAA, the Department of Transportation and the Department of Defense to focus attention on problems related to aging aircraft are being coordinated to improve public safety.

The present paper describes the NASGRO 3.0 software which is well-suited for a comprehensive analysis of defects that may be found in aging aircraft. The predecessor of the current NASGRO computer program for fatigue crack growth analysis, called NASA/FLAGRO 2.0 [1] was originally developed to analyze space hardware such as the Space Shuttle, the International Space Station and the associated payloads. In the current version, the software was enhanced to suit the needs of the aircraft industry. Major improvements in Version 3.0 are the incorporation of the ability to input aircraft spectra of unlimited size, generation of common aircraft fatigue load blocks, and the incorporation of crack-growth models which include load-interaction effects such as retardation due to overloads and acceleration due to underloads. Five new crack-growth models, viz., generalized Willenborg, modified generalized Willenborg, Constant closure model, Walker-Chang model and the deKoning-Newman strip-yield model, have been implemented. To facilitate easier input of geometry, material properties and load spectra, a Windows-style graphical user interface has been developed. Features to quickly change the input and reanalyze the problem as well as examine the output are incorporated.

The software has been organized into three modules. The crack-growth module is the primary module which is used for crack growth analysis, stress intensity factor computation and critical crack size determination. The second module is based on boundary element analysis and provides the ability to model and analyze complex two-dimensional problems to obtain stresses and stress-intensity factors. The third module in NASGRO is designed to organize and process material data. It allows users to store and curve-fit fatigue-crack growth data. On-line help and documentation are provided for each of the modules. In addition to the popular PC windows version, a unix-based X-windows version of NASGRO is also available. A portable C++ class library called WxWindows was used to facilitate cross-platform availability of the software.

The NASA Fracture Control and Analytical Methodology Panel and the Interagency Working Group (IWG) are charged with guiding and monitoring the developments. The former panel consists of members from each of the NASA field centers and NASA Head Quarters. The latter group (IWG) is comprised of representatives from NASA, the Federal Aviation Administration, the US Air Force, the US Department of Transportation and experts from major aerospace companies such as Boeing, Lockheed Martin, United Technologies as well as specialists from research institutes such as the Southwest Research Institute and the University of Dayton Research Institute.

2. CRACK GROWTH MODELS

2.1 NON INTERACTION MODELS

There are three basic crack growth models in NASGRO for describing the growth behavior of cracks subjected to cyclic loads. They are: 1) NASGRO equation 2) Walker equation and 3) Tabular interpolation of da/DN vs ΔK. Using these three basic approaches, load interaction models such as the Willenborg, Modified Willenborg and the Strip Yield models were formulated.

2.1.1 NASGRO equation

Different elements of this equation were developed by Forman and Newman at NASA, de Koning at NLR and Henriksen at ESA and was first published in [2]. It is given by:

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

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. Explanations of the crack opening function, f, the threshold stress intensity factor, ΔK_{th}, and the critical stress intensity factor, K_c are presented later. This equation provides a direct formulation of the stress-ratio effect. Also, the variations in K_c and ΔK_{th} values can have a reduced effect on the linear region of the curve (by a suitable choice of p, q), which produces a better fit to data. Figure 1 shows the curve fit for the A357 Cast Aluminum alloy along with the crack growth data. This material exhibits a rough fatigue surface unlike most materials. It was not easy to fit this data with the usual values of q - a much larger value of 2.0 was needed to enhance the effect of $K_{\max}$ on the crack growth rate thus achieving a reasonable fit. Also the value of C_{th} had to be somewhat larger. This indicates the ability of Eq. (1) to fit the crack growth data for a variety of materials.

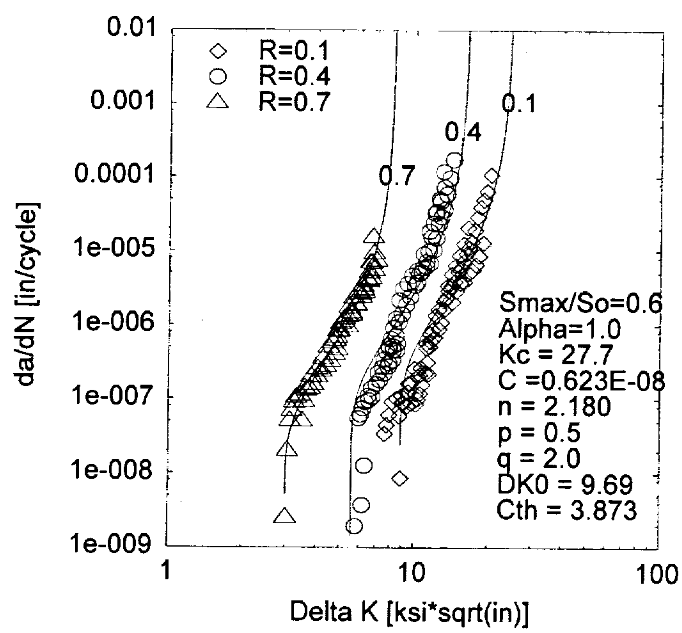

Figure 1 – Curve fit to Equation 1 for A357 Cast Aluminum

NASGRO 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 [3].

The threshold stress intensity factor range in Eq. (1), DK_{th}, is approximated as a function of the stress ratio, R, the Newman closure function f, the threshold stress intensity factor range at R = 0, DK_0, the crack length, a, and an intrinsic crack length, a_0, by the following empirical equation:

$$\Delta K_{th} = \Delta K_0 \left(\frac{a}{a+a_0}\right)^{1/2} / \left(\frac{1-f}{(1-A_0)(1-R)}\right)^{(1+C_{th}R)} . \tag{2}$$

This is a modification of the previous formula, involving the arctan function, that takes into consideration the small crack effect demonstrated by Tanaka, et al. [4]. The present form of the equation allows the spread for various R ratios to be controlled much better using the parameter C_{th}. Values of C_{th} and DK_0 are stored as constants in the NASGRO materials files, and a_0 has been assigned a fixed value of 0.0015 in. (0.0381 mm).

2.1.2 Walker-Chang Equation

The following equations define the basic Walker-Chang equation [5].

For $\Delta K > \Delta K_{th}$, $R \geq 0$

$$da/dN = C\left[\Delta K/(1-\bar{R})^{1-m}\right]^n$$

$$R < R^+_{cut},\ \bar{R} = R \tag{3}$$

$$R > R^+_{cut},\ \bar{R} = R^+_{cut}$$

For $\Delta K > \Delta K_{th}$, $R < 0$

$$da/dN = C\left[(1+\bar{R}^2)^q K_{max}\right]^n$$

$$R \geq R^-_{cut},\ \bar{R} = R \tag{4}$$

$$R < R^-_{cut},\ \bar{R} = R^-_{cut}$$

For $\Delta K < \Delta K_{th}$,

$$da/dN = 0 \tag{5}$$

In the above equations, R^+_{cut}, R^-_{cut} are the cutoff values for positive and negative stress ratios. The threshold stress intensity factor range for this model is determined using

$$\Delta K_{th} = (1 - A\,R)\Delta K_o \tag{6}$$

A being a material constant.

2.1.3 Tabular Input

There are many material/environment combinations for which the fatigue crack growth rate data may not quite fit the above two models. In such cases, direct input of the tabular data for various stress ratios for use in the crack growth routines will greatly increase the accuracy of predictions. NASGRO provides for 1-D tables which accept growth rate versus effective range of the stress intensity factor data and two types of 2-D table input. The first type requires that the da/dN values be identical for each of the R ratios whereas the second type of input allows independent values of da/dN vs Delta K for each R ratio. The latter table is internally converted to the former and used in the interpolation process. There is also an option in the windows interface to allow users to enter an arbitrary crack growth equation. A table is generated using such an equation and can be used in the crack growth computations.

2.2 LOAD INTERACTION MODELS

2.2.1 Generalized Willenborg Model

The Generalized Willenborg model, based on Gallagher's [6] generalization of Willenborg's [7] original development, was incorporated into NASGRO 3.0. This model deals with crack retardation effects only and the details of the formulation are given in [6].

The effect of current loading on crack growth is known to be influenced by the load history; the term "load interaction" describes the interplay of these influences. The Generalized Willenborg model, utilizes a residual stress intensity, K_R, which determines the effective stress ratio due to a load interaction which in turn is used in the crack growth equation and has the effect of retarding the crack growth. Since K_R depends on threshold which in turn depends on R_{eff}, an iterative scheme has been developed and used.

The retardation for a given applied cycle of loading depends on the loading and the extent of crack growth into the overload plastic zone. Details of the formulation may be found in [6, 7, 8]. The constraint factor used in computing the plastic zone size is taken from a fit developed by Newman [9].

2.2.2 Modified Generalized Willenborg Model

A load interaction model termed the Modified Generalized Willenborg (MGW) Model was developed by T. R. Brussat [10] of Lockheed Martin. Based on this, a computer model was developed and incorporated into NASGRO 3.0.

The MGW model extends the Generalized Willenborg load interaction model [6] by taking into account the reduction of retardation effects due to underloads. The MGW model (like the Generalized Willenborg), utilizes a residual stress intensity, K_R, which determines the effective maximum and minimum stress due to a load interaction. The equations are:

$$
\begin{aligned}
K_{\max}^{eff} &= K_{\max} - K_R \\
K_{\min}^{eff} &= Max\{(K_{\min} - K_R),0\}, \quad for\ K_{\min} > 0 \\
&= K_{\min} \qquad\qquad\qquad\quad for\ K_{\min} \le 0
\end{aligned}
\tag{7}
$$

These effective stress intensity factors are used instead of the actual $K_{\max}, K_{\min}$ within the crack growth equation and have the effect of retarding the crack growth. In addition, an underload (i.e., a compressive or tensile load that is lower than the previous minimum load subsequent to the last overload cycle) can reduce such retardation. The stress ratio R_U given by $S_{UL} / S_{\max}{}^{OL}$ (the ratio of current underload stress to overload stress) is used to adjust the factor ϕ . The factor ϕ used to achieve the reduction in retardation is given by

$$\begin{aligned} \phi &= 2.523\phi_0 / (1.0 + 3.5(.25 - R_U)^{.6}), \quad R_U < 0.25 \\ &= 1.0 \qquad\qquad\qquad\qquad\qquad\quad , \quad R_U \geq 0.25 \end{aligned} \tag{8}$$

The parameter ϕ_0 is the value of ϕ for $R_U = 0$. Parameter ϕ_0 is a material dependent parameter that can be determined, ideally, by conducting a series of typical aircraft spectrum tests. The value of ϕ_0 ranges typically from 0.2 to 0.8.

2.2.3 Walker-Chang Willenborg Model

Another load interaction model implemented into NASGRO 3.0 is the Walker- Chang Willenborg model used in the B-1 program at Rockwell. Chang and Engle [5] developed a version of the Generalized Willenborg model which takes into account the acceleration due to negative loads. The formulation was computerized into a code named CRKGRO at Rockwell under contract from US Air Force. They use the Walker-Chang equations as given earlier(equations (3)-(6)). The retardation effects are modeled as in the case of Generalized Willenborg. Whenever the Willenborg load interaction model is invoked, the effective stress ratio R_{eff} is computed and used in the above equations.

2.2.4 Constant Closure Model

This crack growth model was originally developed at Northrop and was used on the B-2 program. It is a simplified closure model based on the observation that for some load spectra the closure stress does not deviate substantially from some stabilized value. This stabilized value is determined by assuming that the spectrum has a "controlling overload" and a "controlling underload" that occur often enough to keep the residual stresses in the crack wake constant, and thus the closure level constant. The closure level can be determined in three ways. Firstly, it can be calculated from a function that is an empirical fit of test data. The fit usually has three segments of which two are straight line segments joined in the middle by a relation using the Walker crack growth law. The user provides the fitting constants. Secondly, the closure level can be entered directly. Thirdly, Newman's closure function may also be used to calculate the closure level. This model is available for the NASGRO equation or a 1-D or a 2-D table look-up.

2.2.5 Strip Yield Model

A Strip Yield Model also has been incorporated in NASGRO 3.0. This model was created by the European Space Agency (ESA) and the National Aerospace Laboratory (NLR) in the Netherlands in cooperation with the NASA Langley Research Center and the NASA Johnson Space Center. The NLR report [11] contains details of the model and its implementation into NASGRO. Strip Yield is a mechanical model based on the assumption that a growing fatigue crack will propagate through the crack tip plastic region, and that this plastic deformation left in the wake of the crack will contribute to stress interaction effects such as stress-level dependence and crack growth rate acceleration and retardation.

3. CRACK GEOMETRY

An extensive library of crack geometries is provided in NASGRO. The crack cases are classified into through cracks, embedded crack, surface cracks, corner cracks, standard specimens and tabular inputs. Plates, cylinders and spheres are some of the configurations that can be modeled. The stress intensity factor solutions for these cases were obtained by various means and have been documented in reports and journal articles. In quite a few cases, detailed finite element models were used to obtain the solutions for the full range of geometric parameters. Such solutions have been built into NASGRO in the form of either fitted equations or tabular interpolation.

To analyze problems with combined loading, NASGRO allows up to four stress quantities. The stress intensity factor is expressed as:

$$K = \left[S_0 F_0 + S_1 F_1 + S_2 F_2 + S_3 F_3\right]\sqrt{\pi a} \tag{9}$$

The stress quantities S_0, S_1, S_2, and S_3 are usually the applied tension/compression, bending in the thickness and width directions, and pin bearing pressures respectively, F_0, F_1, F_2, F_3 being the corresponding geometry correction factors.

4. FATIGUE LOAD SPECTRA

The basic unit of fatigue loading in NASGRO is a schedule. The load schedule concept provides flexibility by allowing the user to repeat blocks and/or combine different blocks together. This is especially useful for analyses of parts that are subjected to both pre-flight testing and flight loads. In addition, the load schedule method provides a means for entering larger spectra. A load schedule is created by filling up to 9999 blocks with different block cases. Up to 20 different block cases can be combined, ordered, and/or repeated within these available blocks. Each distinct block case can contain up to 200 load steps when stored in the SCHDLE file, where a load step is defined as any number of cycles (up to 999,999,999.99) of stress alternating between two specified limits. For aircraft applications when each block is stored in a separate file either in standard NASGRO format or in sequential form, there is no restriction on the number of load steps.

The loading spectrum for payloads, which experience stresses associated with the launch and landing of the Space Shuttle, is provided in the SCHDLE file. This spectrum was developed at the Goddard Space Flight Center (hence the name GSFC) and is reported in reference [12]. It is used for analysis of primary, load-carrying payload structures in the Space Shuttle Orbiter payload bay.

5. BOUNDARY ELEMENT METHOD

This section describes the NASBEM (NASA Boundary Element Method) computer program, a tool for fracture mechanics and stress analysis of two-dimensional elastic bodies of arbitrary geometry and loading, with or without cracks, and multiple zones of different materials.

Although transparent to the user, NASBEM consists of three parts: a user-friendly data input interface, the boundary element method (BEM) computational engine which also contains the stress-intensity factor calculation code, and a post-processing stress analysis component with optional graphical output.

The boundary element computational engine was furnished by researchers at the University of Texas as part of their FADD (Fracture Analysis by Distributed Dislocations) computer code. In this BEM, cracks are modeled by point dislocations and any external and internal boundaries are modeled by conventional boundary elements [13].

The program may be used to compute stresses in bodies that are free of cracks. In the case of multiple zone bodies, stresses can be computed in any of the zones that are crack-free. Special means have been used to overcome the "boundary layer" effect [14], the decay in accuracy in stress and strain as the boundary is approached that is commonly experienced with boundary element techniques. The stress computing algorithms have been tested on several geometric shapes and found to yield acceptably accurate values at all locations within the bodies up to and including their boundaries.

The program allows the specification of points for computing stresses in one of three ways: (a) point by point, (b) straight (or parabolic) line, and (c) circular arc subtending any angle about any point. The output is presented in tabular form or plotted as a function of distance (or angle) along the line (or arc) of interest.

In developing expressions for stresses that are valid for all locations within a body, three regions have been considered: (a) the interior, (b) the boundary, and (c) a narrow boundary layer adjacent to the boundary elements. Different sets of stress expressions are employed for each of these regions. For a point in the boundary layer, stresses are obtained by interpolation between proximal boundary and interior points.

6. MATERIAL PROPERTIES

A major strength of the NASGRO software is its large database of fracture mechanics and fatigue crack growth properties, mainly for aerospace alloys and for some generally used metallic materials. The fracture mechanics data which have been curve fit for this release of NASGRO are contained in a database that includes approximately 6000 sets of fracture toughness data and about 3000 sets of crack propagation data [15]. The list of references for the fracture mechanics data includes Hudson's Compendium [16] and the Damage Tolerant Handbook [17]. The remaining references were taken from miscellaneous published reports and journal articles. Curve fit constants to Eq. (1) were generated for over 300 different material-environment conditions and have been entered into the NASGRO material files. For a complete description of the curve fitting methodology and a comparison of the curve fits with the crack growth data, see reference [18].

7. GRAPHICAL USER INTERFACES

New graphical user interfaces (GUI) have been built for each of the three modules to guide the users in a Windows environment to create batch files and to facilitate easy input of fatigue crack growth data. In the case of NASFLA module, a number of pull-down menus along with timely presentation of the figures of crack geometries makes the input very intuitive. Under windows 95, the user can directly proceed to execute, once the necessary data have been entered. The results of analysis presented in text and graphic form can also be viewed by using menu choices in the post-processing menu. The NASBEM and NASMAT modules also have suitable menu choices and dialog boxes to facilitate input.

8. FUTURE ENHANCEMENTS

Several enhancements are planned for the next version, NASGRO 4.0. Among these are: expanded and improved material properties, additional crack cases that will include weight functions for corner cracks and surface cracks, elastic-plastic fracture mechanics methods, environmentally assisted crack growth models and a comprehensive three-dimensional boundary element module. The 3-D boundary element module will include contact analysis, load redistribution due to crack growth and multiple site damage analysis. Advances in computer technology will also be utilized to make the software more user-friendly and efficient.

9. SUMMARY

A description of the NASGRO software for damage tolerance analysis of aging aircraft is presented. The newly revised Version 3.0 has many features specifically implemented to suit the needs of the aging aircraft community. NASGRO was originally developed to analyze space hardware such as the Space Shuttle, the International Space Station and the associated payloads. In the current version, the software was enhanced to suit the needs of the aircraft industry. Major improvements in Version 3.0 are the incorporation of the ability to read aircraft spectra of unlimited size, generation of common aircraft fatigue load blocks, and the incorporation of crack-growth models which include load-interaction effects such as retardation due to overloads and acceleration due to underloads. Five new crack-growth models, viz., generalized Willenborg, modified generalized Willenborg, Constant closure model, Walker-Chang model and the deKoning-Newman strip-yield model have been implemented. To facilitate easier input of geometry, material properties and load spectra, Windows-style graphical user interfaces have been developed for each of the three modules.

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