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PROGRESS IN THE ANALYSIS OF JET ENGINE BURST-ROTOR CONTAINMENT DEVICES

R. Bruce McCallum
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Prepared for
AEROSPACE SAFETY RESEARCH AND DATA INSTITUTE
LEWIS RESEARCH CENTER
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28

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FOREWORD

This report has been prepared by the Aeroelastic and Structures Research Laboratory, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts under Grant No. NGR 22-009-339 from the Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio 44135. Mr. Patrick T. Chiarito of the Lewis Research Center served as technical monitor and Mr. Richard H. Kemp as technical advisor.

The cooperation of Mr. P.T. Chiarito and Mr. R.H. Kemp throughout this research program is much appreciated. Also, the authors gratefully acknowledge the valuable advice and assistance of Drs. T.H.H. Pian and L. Morino of the MIT-ASRL. The authors are also deeply indebted to Messrs. A.A. Martino and G.T. Mangano of NAPTC, Philadelphia for helpful discussion and experimental results.

ABSTRACT

A FORTRAN IV computer program is presented, which can be used to predict the large two-dimensional elastic-plastic dynamic deformations of a free, nonuniformly heated circular ring subjected to an initial impulse loading followed by a time-dependent forcing function which could be defined to simulate the forces which result from the interaction of a burst-rotor blade and a containment ring. Provisions which account for temperature-dependent material properties and effects of temperature-induced thermal stresses are included. Temperature-dependent, strain-hardening, and strain-rate effects of the ring material are taken into account.

In addition, a new method which uses measured ring position data obtained from high-speed motion picture film is proposed to calculate the approximate "external forces" acting on the ring caused by a fragment-ring interaction. The required accuracy in position measurements to obtain meaningful forces is presented together with resulting example forces.

CONTENTS

CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

SECTION I

INTRODUCTION

1.1 Organization

The Introduction consists of four additional subsections. In Subsection 1.2 the containment/control problem is defined, while possible solutions to the problem are discussed in Subsection 1.3. Subsection 1.4 is devoted to discussing the general design procedure for a containment/control device and how experimental and analytical data may be used to support the design phases for such a device. Some of the experimental and analytical work accomplished to date and paths for future exploration are described in Subsection 1.5.

1.2 The Nature of the Problem

The turbojet engine in wide use today has proven itself to be the most reliable and trouble-free aircraft engine in the history of aviation. Yet, the uncontained failure of high-speed rotating turbojet engine parts, due either to an undiscovered fault in the engine, or catastrophic ingestion of foreign matter, is a well-documented problem [1, 2, 3, 4, and 5].* In fact, Ref. 4 indicates that 93 uncontained engine failures were experienced in the commercial-aviation field during the period extending from 1962 to 1968. In addition, the U.S. Navy experienced 46 failures from fiscal year 1960 to mid-fiscal year 1968. The possibility of just one commercial airliner with hundreds of passengers aboard crashing because of an uncontained engine failure is sufficient incentive to search for a solution to this problem.

*Numbers in brackets, [ ], refer to references cited at the end of the text.

Auxiliary power units (APU's) must also be considered as potential sources of hazardous fragments as these machines, containing high-speed rotating parts, are frequently installed in the fuselages of aircraft, and are approaching the size of turbojet engines in current aircraft.

1.3 Potential Problem Solutions

There appear to be three distinct methods of solution to the uncontained failure problem. They are outlined below

(1) Guarantee all of the engine componets to be 100% failure free.

(2) Selectively reject the fragments to a non-sensitive area of the aircraft or to an area away from the aircraft.

(3) Completely contain any and all fragments with a containment device.

It is apparent that the elements of the three methods outlined above may be combined. For instance, it may be possible to contain a fragment until it has lost a large portion of its energy (method 3) and then reject it to a nonsensitive location (method 2).

The first method is not considered further in this report because it is felt that even with 100% failure-free components the ingestion of foreign objects may certainly cause a potentially uncontained failure.

The second method, that of selective rejection (or deflection) requires further study. Little effort has been concentrated in this area to date, primarily because priority has been assigned to the study of complete rings (and complete containment). It should be pointed out that as far as theoretical analysis is concerned, the selective-rejection device does not appear to be more complicated than the complete-containment device. Proponents of the selective-rejection device suggest that there may be a weight saving over the complete containment device because of the smaller included angle (less than 360°) which it must subtend.

The third method, complete containment, has received most of the attention to date. Research in this area is being conducted by three general groups of people: (1) the engine manufacturers, (2) the Naval Air Propulsion Test Center, and (3) the Aeroelastic and Structures Research Laboratory of the Massachusetts Institute of Technology; research in the latter two organizations has been under NASA sponsorship. More will be mentioned in Subsection 1.3 about the experimental contribution of NAPTC and the analytical contributions of MIT-ASRL. The goal of both of their efforts is to generate data which will be useful in the design and/or evaluation of proposed containment/control devices.

The available evidence suggests that the engine manufacturers have been primarily concerned (in the area of containment) with complying with the FAA requirement that failed blades must be contained.

1.4 The Necessary Steps in the Design of a Containment-Control Device

These steps may be listed conveniently as follows:

(1) First, the nature of the fragments which are to be contained or otherwise controlled must be adequately specified. This includes, but is not limited to, knowing the mass, rotational velocity, translational velocity, all geometric properties, and pertinent constitutive-property data of the fragment materials. The design must be oriented toward dealing with particular types of fragments. Portions of a fan blade from a large turbofan engine pose a different problem than does a blade from a compressor or turbine rotor.

(2) Once the properties of the fragments are known, a trial containment/control device configuration can be chosen, based on experimental and/or analytical evidence. The word configuration is understood to include cylinders, rings, and other useful structural shapes.

(3) Next a material or combination of materials for the device is chosen on the basis of experimental and/or analytical evidence.

(4) Either by analysis or by experimental evidence, the geometric parameters of the proposed containment/control device can be optimized (to minimize weight, for example).

(5) Steps 3 and 4 are repeated for each material which may be under consideration, and steps 2, 3, and 4 are repeated for each configuration under consideration.

(6) On the basis of the above procedure, the design process continues by, hopefully, an efficient process, until a final configuration is chosen.

It is clear that the design procedure must rely heavily on either (a) experimental data or (b) analytical techniques, or a combination of both of these techniques.

1.5 Experimental and Analytical Aspects

1.5.1 Experimental Investigations

At the present time much of the research conducted in the United States is experimentally oriented. It appears that the engine manufacturers have been successful in meeting the FAA blade-containment requirements. At present, this blade containment is being accomplished with the engine casing. The casing parameters are thought to be determined mainly or entirely from consideration other than containment requirements. In other words, the casing is not blade-containment critical. It is believed that ballistic-penetration data are used to check proposed casing designs for blade-containment. Aside from the above, the authors lack more specific knowledge as to the exact design methods used by engine manufacturers in solving the blade-containment problem.

The Naval Air Propulsion Test Center, Philadelphia, Penn. has one of the most advanced and well-equipped spin-pit testing facilities in this country. For approximately the last four years, experiments on various forms of containment rings have been carried out at NAPTC. Some of these rings, consisting of various materials and material combinations, have been submitted to NAPTC by industry and some are of their own design. Many of these experiments have yielded excellent high-speed motion pictures of the extremely-short-duration ("violently explosive" in nature) events occurring during each test. These exploratory investigations have contributed to the understanding of the phenomenology of the containment problem. It does not appear that there are sufficient data at the present time to permit their organization into a form which will be of definitive assistance to the designers of new containment devices. However, the data and valuable experience gained by NAPTC personnel have been helpful in the preliminary stages of particular containment-device designs in certain instances.

1.5.2 Analytical Investigations

Personnel of the Aeroelastic and Structures Research Laboratory, M.I.T. are engaged in conducting analyses associated with the containment/control problem. The goal of this research is to establish analytical techniques and mathematical models of a burst rotor, for example, and typical containment/control configurations so that the analysis, design, and optimization of containment/control devices can be accomplished as efficiently as possible.

The analysis of the ring configuration was chosen as the starting point, since definite experimental evidence about transiently-deforming rings is comparatively easy to obtain and to compare with analytical results. The ring analysis is embodied in the FORTRAN computer program JET 1 which is described in detail in Section 2 of this report. Assuming that the forces acting on the ring (caused by the fragments, in this case) are known from appropriate estimates or other means, JET 1 will compute the transient elastic-plastic large-deformation response of the ring. The output information includes deflections, strains, stresses, and bending moments.

It should be noted that JET 1 requires, as input, the forces acting on the ring caused by the fragment(s) interactions with the ring. The primary difficulty is that these forces are not known a priori. It is believed, however, that an approximate forcing-function model may be deduced from the physics of the problem and may be expressed in terms of the containment/control device geometry, material properties, and parameters associated with particular types of fragments. Very little progress has been made in this area to date since the MIT-ASRL effort thus far has been devoted largely to devising experiments and data solution procedures to aid in increasing the knowledge of the nature of these forcing functions in a typical rotor-burst problem.

Accordingly, a series of five experiments was designed to be conducted at NAPTC. In these tests, different types of fragments are to be used; a simple single-layer containment ring is to be employed in all of these initial tests. In the first (and "simplest") test, a single blade is "failed" and impacts the containment ring. The transient response* of the containment ring is recorded with a high-speed framing camera. The trajectories of 72 points along the midsurface circumference of the ring are then measured for each test. These trajectories may be substituted into the equations of motion of the ring in order to deduce the forces (or the forcing function) acting on the ring. The computer program which accomplishes this "force extraction" is called TEJ 1,

*In addition to photographically recorded deformations, strains are being recorded at various locations on the outer surface of the ring.

and its use is described in Section 3. It should be emphasized that the same basic equations are embedded in TEJ 1 as are used in JET 1, only the inputs are different.

In summary, the following serves as a condensed guide to the current and planned MIT-ASRL research relating to the understanding and analysis of devices for the containment or control of rotor fragments:

(1) Approximate forcing function models are to be devised from the physics of the problem, using fragment size, fragment kinetic energy, etc., as variables.

(2) Photographic results from NAPTC experiments will be employed to obtain detailed response measurements of a containment ring for the purpose of checking and/or modifying the approximate-force prediction methods under item (1).

(3) Substitute the position results obtained from (2) into TEJ 1 and deduce fragment-ring interaction forces.

(4) Compare the calculated forces from (3) with estimated forces from (1) and modify the approximate analysis in (1) as needed.

(5) Independently and concurrently, apply the forces from (1) to JET 1 to predict ring responses and compare these results with results obtained from (2).

The research effort emphasis thus far has been given to items (2) and (3). In the continuing research effort, all five items will be pursued in detail. In addition, dynamic response analysis methods and programs should be developed to treat multilayer, multimaterial configurations which may be useful for containment-control purposes.

The remainder of this report consists of three sections: Section 2 describes the computer program JET 1 and reports the results of three studies using JET 1. A new analytical method for finding the forces acting on a containment ring resulting from a particle impact, using position data obtained from high-speed motion pictures of controlled laboratory spin-pit tests is presented in Section 3. A summary of the work accomplished to date, and recommended avenues of further study are given in Section 4.

Appendix A presents the equations of motion used in the computer program JET 1. Appendix B is a user's manual for JET 1 and contains the program listing and a sample problem with resultant output.

SECTION 2

CAPABILITIES OF THE JET 1 COMPUTER PROGRAM

2.1 Introduction

JET 1 is a computer program which uses a step-by-step numerical integration method for predicting the large-deflection dynamic elastic-plastic response of a single-layer ring. This method is based on a finite-difference representation of the partial differential equations of dynamic equilibrium [6, 7]. JET 1 is especially tailored to predict the elastic-plastic dynamic response of a ring to impulsive initial loadings and/or subsequent external transient loads as might be caused by fragments from burst high-speed rotating parts of jet engines colliding with the ring.

The program assumes a uniaxial stress state, and can account for elevated, nonuniform temperatures (varying both circumferentially and through the thickness) in the single-layer ring. The ring material may be elastic, strain hardening, and/or strain-rate sensitive, and is assumed to have material parameters which are temperature dependent. Thermal stresses resulting from the imposed temperature distribution are accounted for in the initial conditions. Provisions are made for including various peripheral distributions of initial impulsive loading and for simple distributions and time histories of subsequent external forcing functions. Also, provisions are available for damping out the elastic portion of the ring response due to the initial thermal stresses, if desired.

2.2 Description of the Program

2.2.1 Assumptions

The following conditions and/or assumptions are made for the JET 1 program:

1. The stress-strain curve corresponding to any given temperature of the single-layer ring material is the same for both tension and compression.
2. The ring cross section is uniform around the circumference and is rectangular in shape.
3. The ring can be represented by a series of discrete masses, one at each station, interconnected by straight weightless bars.
4. Plane sections remain plane in bending.
5. Material behavior can be elastic, strain-hardening according to the mechanical sublayer or subflange model given in Ref. 7; strain-rate effects can be included (see A.5c in Appendix A).
6. The temperature distribution of the ring is considered to be constant with time during the run. (However, each continuation run can have a different time-independent temperature distribution in order to approximate prescribed, quasi-steady varying temperatures, if desired.)
7. The procedure employed for obtaining the static solution for the heated ring is to allow the ring to respond dynamically to the initial stresses induced by the temperature distribution until all of the plastic work has occurred. Then, the elastic response can be artificially damped out to obtain the final stress distribution and ring shape.

2.2.2 Program Capabilities

2.2.2.1 Temperature Distribution Descriptions

The temperature distribution of the ring is specified in JET 1 by assigning a value of temperature to prescribed stations* through the thickness direction of the ring's cross section for

*Such stations are termed "flanges" or "flange locations".

each mass point around the ring circumference. Because it may be unnecessarily tedious to read in values of temperature vs circumferential and depth locations, several alternate methods are offered in JET 1 for specifying temperature distributions which are either of a uniform nature, or of the type that can be described analytically as a function of circumferential position. The three options available in JET 1 for describing the temperature distribution are as follows (Note: the three methods termed A, B, and C are accompanied, in the left-hand margin, by a code name* set equal to some integer; these integers, when specified in the input data, tell the computer what method is to be used.):

METHOD A

LISTEM = 1 — The temperature distribution is described completely with input cards (see Fig. 2a).

METHOD B

LISTEM = 2 — The temperature distribution is of the type that can be described (see Fig. 2b):

(1) through the ring thickness by either

IRAID = 0: reading temperature vs thickness by input cards, or

IRAID = 1: assuming a parabolic distribution of the type

$$T(K) = \frac{T_o}{H^2} \left(\zeta(K) - \frac{H}{2}\right)^2 - \frac{T_1}{H} \left(\zeta(K) - \frac{H}{2}\right) + T_2 \qquad (1)$$

where $\zeta(K)$ is the radial distance from the Kth flange to the c.g. of the ring's cross section

H is the ring thickness

T_o, T_1, T_2 are input values.

(2) circumferentially, by assuming that

---

*Variable names used in the computer program are listed and described in Appendix B, Subsection B.6.

any of the above selected variations of temperature through the thickness

ICIRC = 1 is constant around the circumference

ICIRC = 2 varies as sinθ*

ICIRC = 3 varies as cosθ/2

METHOD C

LISTEM = 3 Yields a temperature distribution which is geometrically a function of the distance from the flange to the outer surface of the front of the ring measured parallel to the z axis (see Fig. 2c). The temperatures are obtained from a curve of temperature vs material depth which is read in as input data in terms of ten temperature vs material-depth coordinates. The program then calculates the value of material depth corresponding to each flange position and reads the appropriate value of temperature, interpolating linearly between the proper coordinates given. This procedure is used only for the front of the ring and that portion which is outside the plane tangent to the inner radius, parallel to the z axis (see Fig. 2c). The temperatures of all portions of the remainder of the ring are set equal to the unheated temperature of the ring: TCOOL.

2.2.2.2 Specification of Temperature-Dependent Material Properties

The pertinent temperature-dependent material properties of the ring are calculated in the program for each flange corresponding

*See Fig. 1 for the nomenclature used with the lumped-parameter model.

to the flange temperature by employing an interpolation scheme (see Fig. A.5c) which uses coordinates of experimentally-obtained curves of each material property vs temperature. Thus, the program reads in values of material properties at given temperature levels (the upper and lower temperature extremes must bracket all the given temperatures of the ring) and then calculates, by linear interpolation, appropriate material constants for each flange at each mass point of the ring.

2.2.2.3 Types of External Loadings

The current input provisons of the JET 1 program assume that the ring is acted upon only by a single "fragment" and thus the options available to the user to describe the initial impulse and the subsequent forcing function are tailored especially to this type of loading.* The options available to describe these loadings are listed below. A code name is given in the left-hand margin to identify each possible loading condition:

1. The initial impulse is specified by reading in or calculating the initial velocities in one of 2 ways (see Fig. 3):

   IOTA=1 The discrete impulse on each mass point is fixed by assigning initial radial and tangential velocity components.

   IOTA=2 A sine-shaped velocity field is specified to be distributed over a given number of mass points oriented at a constant given angle to the local ring tangent.

2. The subsequent time-dependent forcing function in JET 1 is described in the form of a triangular pulse as shown in Fig. 4. This time-varying total force is distributed over a given number of masses in the form of a half sine wave, and the position on the ring at which the forcing

* The user may add other options readily, as his needs dictate, since JET 1 is valid for any type of forcing function once provision for its input has been made.

function is applied can move at a desired rotational velocity to simulate a possible motion of a particle after its initial impact upon the ring. Finally, the angle at which the forces are applied is assumed to be constant and is defined as an input quantity.

2.2.2.4 Artificial Damping of Ring Response

Provisions are included in the JET 1 program to allow the user to damp out the ring motion artificially when desired. This is done by calculating a force (for each mass point) which is proportional to the local velocity, and subtracting this damping force in the equilibrium equation. The purpose behind the need for damping the motion stems from the fact that the ring will respond dynamically from an imposed nonuniform temperature distribution and and will continue to vibrate elastically (after plasticity, if present, has been completed) for as long as the program is run, unless damping is introduced. Since it is usually assumed, in practical applications, that the heated ring is stationary (although deformed, with an internal stress distribution) when external forces are applied, it is useful to be able to solve for the static ring shape and stress distribution under these thermal conditions, before one takes into account subsequent externally-applied forces. Because the energy removed from the ring by plastic work is path-dependent, it is important to impose artificial damping only after the plastic work has been completed. Also, it should be noted that the value chosen for the artificial damping constant must be less than the "critical damping" value in order not to affect the final ring shape; on the other hand, the damping should not be too small, so as to keep the computer time to a minimum.

In the JET 1 program, both the starting time for imposing artificial damping and the damping constant can either be specified, or if either or both values are set equal to zero, the program will make appropriate estimates for each of these two quantities based on the structural properties of the ring. This capability is described in greater detail in Subsection B.2.1 of Appendix B. The ring is considered to be completely damped when the maximum kinetic energy over a 100 cycle interval is 0.1% of the maximum kinetic energy present before damping began.

2.2.2.5 Program Capacity

The JET 1 program is capable of accommodating the following:

1. The single-layer ring can be divided into a maximum of 100 mass (circumferential) stations.
2. The total number of flanges through the thickness must be an even number, and must not exceed 10.
3. The total number of subflanges* per flange to simulate a general stress-strain curve must not be more than five.
4. The total number of temperature levels at which material properties are given for estimating ring temperature-dependent material properties cannot be greater than five.
5. The main computer programs will accommodate any type of forcing function; however, the only input subroutine written to date is for a "single fragment".

The number of memory locations required on the IBM 360-65 at MIT to run JET 1 as listed in Appendix B is approximately 175,000 bytes. This includes the locations required for the MIT computer library subroutines.

2.2.3 Program Terminology and Arrangement

The JET 1 program is composed of a main program and 17 subroutines which appear in the program in the order listed. The names and functions of these programs are as follows:

MAIN The main program applies only to a free, single-layer, circular ring. It supplies the overall

*Note that each flange of a given mass point consists of up to 5 equally-strained subflanges of elastic-perfectly plastic material; each subflange has the same elastic modulus, but a different yield stress in order to represent strain-hardening behavior of the material.

logic for calling the subroutines and determines the values for damping and for the maximum required running times when these values are not supplied. The input and output logic tape units used by the computer are also specified in MAIN. These names MREAD, MWRITE and MPUNCH must be given values corresponding to those required for the user's computer facility.

INPUT The ring geometry, program logic terms, damping values, and program cycle time are all read by this subroutine. Also, additional quantities (derived from the input data) which remain constant through the program are calculated here.

TEMPS Subroutine TEMPS reads in the required temperature information and defines the temperature distribution of the ring.

HEAT The temperature-dependent material properties of the ring are defined from input information in this subroutine. Elastic stress limits and subflange areas (weighting factors) are also defined here.

TEMPUS The minimum and maximum effective values, depending on the temperature distribution, of the elastic modulus are calculated in TEMPUS. This subroutine will also calculate the appropriate time increment DELTAT, if the input value is set equal to zero in INPUT.

INIT INIT calculates the initial mass point coordinates, establishes the pertinent boundary conditions, and initializes most of the variables used in the subroutines.

IDENT The IDENT subroutine is called early in the program to print out the values of certain input parameters, including the temperature distribution, in order to identify the run being made.

CYCLE — CYCLE calls the subroutines which carry out the actual solution for the desired problem for each time cycle. This subroutine is called cyclically until the final results are obtained.

STRESS — This subroutine contains the stress-strain relations. The STRESS subroutine can be used for temperature-sensitive materials which exhibit elastic strain-hardening properties, with or without strain-rate behavior.

STRAIN — The strain-displacement relations described in Appendix A are contained in this subroutine.

IMPULS — The data for the impulsive loading is read by this subroutine. This information is then used to compute the incremental velocities and displacements of the mass points.

PREZZ — This subroutine reads the data pertaining to the time-dependent forcing function and uses these data to compute the forces on the ring.

EQUIL — EQUIL contains the dynamic equilibrium equations that are used throughout the run whether or not external loads are acting on the ring. It computes the work done on the ring by the external forces and the artificial damping forces, and it also computes the lateral momentum change induced by the forces applied to the ring.

KOOLIT — The KOOLIT subroutine computes the average value of ring separation every one hundred program computation cycles and tests these values until a full cycle of the ring's first elastic-plastic mode has been computed. At this point a signal is given to the main program that plastic behavior is considered to have ceased, and artificial damping can begin.

STOP The kinetic energy of the ring is calculated in this subroutine while the ring is being damped, and the maximum value is found for 100 cycle periods. The maximum value of kinetic energy for each 100-cycle period is then compared with 0.1% of the maximum kinetic energy available at the start of damping in order to find when the ring's elastic response has been satisfactorily damped.

RECORD The RECORD subroutine prints out when major milestones have been passed in the program (such as when damping was begun, etc.).

PRINT The relevant energies and the strains on the inner and outer surfaces of the ring are evaluated in PRINT. The ring shape, separation, internal forces, and current time are printed out by this subroutine.

FINAL The subroutine FINAL punches the data cards which can be used to continue a run beyond its programmed termination point. It also reads the input cards in a continuation run.

A complete listing of all the terms used in the JET 1 program is given in Appendix B; a complete listing of these programs is also given in Appendix B.

2.2.4 Organization of MAIN Program

The flow chart given in Fig. 5 outlines the general organization of the JET 1 MAIN program. The first part of the program defines the problem to be solved by reading in constants and calculating other needed quantities. The remainder of the program is divided into two parts. The first is used to solve for the static solution of the heated ring, before external forces are applied, using "artificial" time. The second part takes either the results from the first part with time set back to ZERO, or (in the case of an unheated ring) initial conditions set up in the beginning of MAIN, and solves for the dynamic and, if desired, static solution of the ring with external forces included. The two parts are separated by the value of a variable called JSTART. If JSTART is set equal to zero in the program input, the ring is assumed to have a temperature distribution and the first section is used with artificial time to damp out the ring's dynamic motion caused by the internal thermal stresses. If JSTART is set equal to 1 in the program input, the first section is passed over, and real time starts immediately with or without a temperature distribution, as desired. When a continuation run (using the punched output deck from a previous run) is called for, JSTART is set equal to 1 automatically by the program, and the solution proceeds using real time. Thus, if a temperature variation with time is desired, the second section must be used. The motion of the ring cannot be damped in this part of the program until two conditions are met: first, all external forces must have ceased acting. Second, the amount of elapsed time from the end of external loading to the beginning of damping must be greater than the value of HALT2, which is either given in input or calculated (see description for Card 3 in Subsection B.2.1 of Appendix B) and is the estimated time required for plasticity to end.

2.3 Application of the JET 1 Computer Program to Some Typical Containment Problems

In order to exercise the JET 1 computer program and to demonstrate its capabilities, three exploratory studies were undertaken to compute the large-deflection, elastic-plastic transient response of single-layer metal rings subjected to given distributions of impulse loadings, all at room temperature conditions.

The first study was preliminary in nature and its purpose was to determine the effects of varying certain geometric and material parameters on the transient response of a ring. The forcing function used in the study was a prescribed initial velocity distribtuion which was applied to a 4-degree segment of the ring in an outward direction, 45 degrees to the local normal. The first of eleven computer runs (see Table 1) was designed to approximate in a very rough sense NAPTC-AED Test 10 (Ref. 3) wherein a single turbine blade was made to impact a 15.438-inch diameter, 0.125-inch thick, 1020 steel ring. An initial velocity of 8000 in/sec was used in the first calculation (Run 1); this velocity is equal to the calculated value of the velocity of the blade fragment at impact. Runs 2 through 4 were the same as Run 1, except that the ring thicknesses employed were 0.1375 inch, 0.1500 inch and 0.2500 inch, respectively. Runs 5 and 7 were equivalent to Run 1 except that the resultant initial velocity of the 4-degree ring segment used in each run was 8800 in/sec, 9600 in/sec, and 16,000 in/sec, respectively. Runs 8 through 10 used the same value of the Elastic Modulus (30×10^6 psi) as Run 1, but the strain-hardening stress-strain curve in each case was elevated such that instead of a yield stress of 35,000 psi (as in Run 1), the yield stresses were 38,000 psi, 42,000 psi, and 70,000 psi, respectively. Finally, Run 11 was the same as Run 1 except that instead of using 80 mass points to approximate the ring, 100 mass points were used, and the initial velocity was distributed over about a 10-degree rather than a 4-degree section of the ring, as used in Runs 1 through 10, on an equal-momentum basis. The results of the first run are presented in Fig. 6 which shows the ring profile shape at various instants in time. Figure 7 shows the ring profile for each succeeding case at t = .002140 sec. No specific conclusions are made from this first study, for while instructive, the results are too preliminary in nature to be very definitive. The study does illustrate, however, one type of parametric study for which JET 1 can be used.

The purpose of the second study was to use JET 1 to calculate the value of a characterizing velocity (simulating a single blade impact as in the first study) which would produce incipient fracture of each of three equal-weight rings made of 1020 mild steel, 7075-T6 aluminum alloy, and 6Al-4V titanium alloy, respectively, under various conditions.

Each ring was finite differenced such that 60 mass points represented the entire ring. The initial velocity distribution used to simulate the blade impact was assumed to be sine-shaped, covering 5 segments (30 deg of arc) of the ring. The velocity imparted to each of the 5 masses was directed at an angle β relative to the local tangent (see Fig. 3), where β = 21 deg. for all but the last case where β was varied from 0 to 90 degrees.

The procedural use of JET 1 to calculate the fracture velocity in each case was as follows: the particular physical properties of the ring to be studied were supplied to JET 1, and the ring was excited by a characterizing velocity which was chosen to be higher than that expected to produce incipient-fracture of the ring. For each program finite-difference time-cycle, a test was made by the computer to compare the maximum current value of tensile strain with the prescribed (or input) value for the fracture strain. When the program detected a value of strain greater than this value, the program was restarted with the same initial conditions as before, but with the characterizing velocity decreased by approximately 3 per cent. This cycling of the program continued for each case until the characterizing velocity was reduced to a point at which the peak value of maximum strain during the protracted run was less than the given value for fracture strain. The velocity used before the nonfracture velocity was then chosen as the "critical" initial velocity

The room temperature static mechanical properties [10, 11] used to describe these three materials are considered to be reliable except, perhaps, for the values of the fracture strains and were represented by piece-wise linear segments as defined in

Table 3. The dynamic stress-strain properties used for the 1020 mild steel, and 7075-T6 aluminum rings are considered to be only approximate, but the 6Al-4V titanium dynamic properties used are believed to be reliable [10]. For aluminum and titanium, only static values of fracture strain were used. For mild steel, where the fracture strain is believed to be highly dependent on strain rate, both a static value of fracture strain, and an estimated variable fracture strain as a function of strain-rate were used (Fig. 8). An approximate description for the strain-rate dependent yield behavior of these materials is shown in Fig. 9.

A tabular description of the cases analyzed is presented in Table 2. The ring parameters are presented in Table 3.

Figure 10 presents the calculated values of the initial velocity index, V_o, required to produce incipient tensile structural fracture for each case identified in Table 2 for which β = 21 degrees. Using these results, the following tentative conclusions can be made.

On the basis of the dynamic material property data used for steel (Fig. 9), the inclusion of the strain rate ($\dot{\varepsilon}$) effect on the stress-strain curve (but ignoring the $\dot{\varepsilon}$ effect on the fracture strain magnitude) increases the critical velocity value V_o markedly compared with using static stress-strain properties and static fracture strain values exclusively. Case S3 in Fig. 10 for 1020 steel depicts the (possibly more realistic) result wherein a rough approximation for the $\dot{\varepsilon}$ effect has been included in both the σ,ε curve, and for the fracture strain.

Similar results were obtained for 7075-T6 aluminum, and 6Al-4V titanium as shown in Fig. 10. Were $\dot{\varepsilon}$ dependent fracture strain data available for these two materials, a trend similar to but perhaps less pronounced than that of S3 vs S1 and/or S2 would be expected.

In the vicinity of producing failure strain levels in a titanium ring, the results showed that a 2.3 per cent increase in V_o led to a 10 per cent increase in the maximum strain. Conversely, an uncertainty of 5 per cent in the failure strain would mean an uncertainty of about 1.2 per cent in the critical value of V_o.

Some calculations were also carried out to illustrate the influence of the initial velocity angle β on the location and magnitude of the maximum strain induced in a 6Al-4V titanium ring which was loaded impulsively over 5 mass points as in previous cases. The effect of changing β is shown in Fig. 11 where the calculated inner and outer surface circumferential strains, occurring at the same (also the most critical) location for all the cases, at the same instant of time during each response, is plotted as a function of β. The results are consistent with what one would expect from physical arguments.

The third problem-study reported herein was similar to the second in that the velocity for incipient fracture was sought for different test conditions. Equal weight rings were loaded impulsively as before; however, each of 4 rings was assumed to be made of a different hypothetical elastic, perfectly-plastic strain-rate insensitive material, but all of equal fracture toughness (all materials had the same area under the stress-strain curve to the fracture level of strain). As shown in Fig. 12, the material in Cases 1, 2, and 4 had common elastic modulii, but different perfectly-plastic yield limits. For Case 3, the elastic modulus was reduced by a factor of 100, but the yield limit was chosen to be the same as for Case 1. Comparing Cases 1, 3, and 4, the critical velocity, V_o for incipient fracture shows only a weak dependence upon the yield limit when the material has the same elastic modulus (note that the response is quite nonlinear.) Comparing Case 3 with Case 1, the change of the elastic modulus by a factor of 100 changes the critical velocity by only about 28 per cent.

In conclusion, it should be emphasized that these example calculations are intended only to illustrate the manner in which a parametric study can be made so that the advantages of using one material over another can be compared.

SECTION 3

DETERMINATION OF THE FRAGMENT-RING INTERACTION FORCES FROM EXPERIMENTALLY-OBTAINED POSITION DATA

3.1 Introduction

Extensive results from the use of computer programs using the finite-difference numerical method written in this laboratory (Refs. 6-9) have shown that the transient response of structures acted upon by high-energy, impulse-type forcing functions can be accurately predicted if the structural properties, configuration, and forcing function shape and magnitude associated with the problem are known. Thus, the computer program JET 1, which embodies this finite-difference approach, can be expected to fulfill the requirement of deciding analytically whether a given ring will contain a given jet engine rotor failure, if the above information is known. Perhaps the principal difficulty in the analysis of fragment-ring interaction and structural response concerns the forces which result from the fragment-ring interaction; these forces are not well defined and are difficult to estimate explicitly from the phenomenology standpoint. While it is possible in principle to program the interaction of the fragment and ring on a computer by treating each part as a separate free body and following in detail the elastic and elastic-plastic collision interactions, this method has the disadvantage of being feasible for only one or, at most, two fragments. Any higher number would be prohibitively complicated.

An alternative method of deducing the forces caused by the fragment-ring interaction is proposed in this section. This method will allow these forces to be deduced approximately from position-time data obtained from measurements of the configuration of an impacted ring at a sequence of instants in time. In the computer program JET 1, as currently written, the forces acting on the structure are assumed to be known, and these forces when substituted into the equations of motion via JET 1 yield the transient response. The inverse procedure is also possible: by substituting an observed transient response into the equations of motion, the forces which produced that motion can be deduced. Once the approximate forces are found, they can then be used to evaluate, and possibly help in determining and/or improving future approximate general methods for estimating what the fragment-ring interaction forces would be for other ring-fragment configurations, materials, and impact conditions. Once these general forces are found, they can be used in future parametric studies to determine optimal containment ring parameters for various rotor burst situations.

3.2 Description of the Method Used to Deduce the Interaction Forces

In this method, the equations of motion as used in JET 1 are reversed such that position-time data of the ring are used to estimate the second time derivative of the positions (accelerations) of each of the finite-difference mass points (see Appendix A). These derivatives are used to determine the inertial forces acting on each finite-difference mass point and these, combined with the internal forces, allow the resultant external forces acting on the ring to be calculated. A computer program which embodies this approach has been written and is called TEJ 1.

To evaluate and develop this method, position output from the example JET 1 run, given in Appendix B, using known forces, was used as input to TEJ 1. The results from this preliminary run showed that when exact positions are used, exact forces are calculated by TEJ 1. However, the experimental position data obtained from the high-speed films of the rotor-burst tests are not only too sparse in time* (the computer program requires positions about ten times more closely spaced for a typical ring than the high-speed camera currently employed is capable of producing), but also it is inevitable that errors (and uncertainties) are produced when the film records are reduced to provide digital data for the configuration of the ring.

*The current interval between frames is 28 μsec.

These errors can be demonstrated to have a Gaussian distribution about a mean value, with a characteristic probable error (PE)* inherent with the reduction process [13].

In order to determine a reasonable position measurement accuracy, the Naval Air Propulsion Test Center is currently conducting and photographing, with high-speed cameras, controlled rotor-burst tests suggested by MIT in support of the analytical effort. The high-speed, film strips are viewed on an automated film reader with a sensitivity of 1 micron at the film plane, and the positions of 72 "mass points" on the ring, and 4 background points used to establish an inertial reference frame, are read from each frame to produce a time history of the ring shape after impact. Initial studies show that the position data from these films have an effective probable error of between 0.010 and 0.020 inch on a 7-1/2-inch radius ring.

To investigate what effect these position errors would have on the results from TEJ 1, the exact position-time data discussed earlier were first perturbed with a Gaussian set of random errors with a mean of zero, and a PE as low as 0.0001 inch for the example ring. Linear interpolation was used to supply positions to TEJ 1 between the supplied position data which was spaced in time so that it simulated the film record data. The forces obtained from TEJ 1 using this simulated perturbed, sparse position data showed no recognizable correlation with the "exact" forces which were used as impact data for JET 1.

From these results, it was concluded that either the position data would have to be read much more accurately, or these data would have to be improved substantially by smoothing techniques before they could be used to obtain interaction forces. The latter

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*The probable error of a reading, in a given set, is that magnitude of deviation whose probability of being exceeded is one half. The value (PE) can be calculated from the Standard Deviation (S) as PE = 0.6745 S (Ref. 13).

approach was examined first in order to increase the allowable error in position data for TEJ 1, and a smoothing procedure to be applied to the input values of the position was incorporated into the TEJ 1 program. This procedure and some related developmental experiences are described in Subsection 3.3.

3.3 Analytical Smoothing Methods Used to Improve the Measured-Position Data

As mentioned in the previous subsection, the reduced data that are obtained from the high-speed photographs have two problems associated with them: (a) sparseness and (b) inaccuracy. Many approaches have been tried to find a satisfactory way of not only estimating the mass point positions on the ring required in between the times recorded on film by interpolation but also to improve the position data as a function of space and time by smoothing. The current most successful procedure for improving the position data is described in the following.

The first step consists of smoothing the mass point position data for the ring at each time instant (including assumed initial values before time zero). If, at any time, each x,y mass point coordinate set is plotted against mass point number, then it is possible to generate two smooth curves which describe the shape of the ring based upon the set of measured data in a least squares sense. Because each curve is cyclic in nature (closed ring), Fourier series* were chosen to generate each smoothed curve. Thus, both sine and cosine series Fourier coefficients which together describe the ring shape are calculated at each instant corresponding to the camera framing times.

The next step uses Legendre polynomials to smooth the time-variation of each Fourier coefficient calculated in the first step. Legendre polynomials were chosen for this step because they are

*All interpolation and smoothing methods used in TEJ 1 at present are described in detail in Ref. 14.

applicable to a discrete interval, and the weighting function is unity over the entire interval. Thus, no part of the ring response is accentuated in the evaluation of the smoothed curve. Unfortunately, it is not desirable to use only Legendre polynomials to obtain the final smoothed curve since the number of times at which positions are supplied is generally so low that when higher order Legendre polynomials are used, the resulting smoothed curve becomes "unstable" in the sense that the curve between points makes wide unreasonable excursions from the desired curve. To solve this problem, intermediate values of each Fourier coefficient versus time were supplied using 6-point Lagrangian interpolation polynomials. Interpolation using 6 points was chosen so that for each interval in time between the known Fourier coefficients, three values on each side of the interval could be used to weigh the interpolated curve. (At the beginning and at the end of the response, of course, this cannot be done; in these cases, the center of the 6-point sequence cannot be used.) Once the Legendre coefficients are calculated, the smoothed (in time) values of the Fourier coefficients can be calculated at any time desired, and thus the smoothed x,y mass point positions are obtained, in turn, as required for the TEJ 1 program.

3.4 Preliminary Results

3.4.1 Smoothing Techniques

The various methods tried up to, and including, those presently used in the data smoothing process, were evaluated by using position data in TEJ 1 obtained from JET 1 using known forces. To determine what maximum PE in position data would still yield satisfactory forces, exact position data obtained from JET 1 were perturbed with Gaussian distributed random errors. As the PE of the position data was increased from zero, the resulting forces were observed and compared with the original "exact" forces.

The particular case considered for all testing of TEJ 1 was a 7.3375-in midsurface-radius ring, 0.175-in. thick, 1.0-in. long, made of 6061-T6 aluminum. The forcing function was chosen arbitrarily to be a triangularly-shaped pulse, lasting 400 microseconds with a peak value of 10,000 pounds at t = 200 microseconds. The total force was assumed to be distributed over a 25-degree segment of the ring in the shape of a half-sine wave. The complete ring was finite-differenced into 72 segments (see Subsection B.7 of Appendix B).

When the exact transient response obtained from JET 1 for this example was used in TEJ 1 using 30 Fourier terms (both cosine and sine) and 20 Legendre polynomials, the results closely duplicated the input forces to JET 1. Further runs were made using position data that were perturbed with random numbers having a mean value of zero, and a probable error of increasing value. As the PE was increased, it was found necessary to decrease the number of both Fourier terms and Legendre polynomials used to obtain an optimum force representation. This was not surprising since a high number of terms in the smoothing function tends to make the resultant smoothed curve follow the position errors too closely. A lower number of terms creates a smoother, but less sensitive curve. This trend of using fewer terms as the level of error increases continues until the complexities of the forcing function can no longer be adequately described by a curve which must be overly smoothed so that the errors do not unduly affect the curve shape.

A judged limit of "acceptable" probable error was chosen to be .003 inch. This value was determined by making a compromise between two considerations. Portions of the position data supplied by NAPTC, as described in the following subsection, showed a data accuracy higher than the average value of PE for the whole analysis. The fact that these accuracies were obtained indicated that this level of accuracy might be obtainable for all of the data if the procedures used in reading the data could be improved. On the other hand, the results from TEJ 1 indicated that while it was very desirable to obtain as high an accuracy as possible for the position data, a value of PE equal to the best obtained from the error analysis performed on the NAPTC data would still yield useful force data. Thus, the chosen value of PE (0.003 inch) on the example ring was a compromise between two rather indefinite limits (the measuring error of PE = .015 inch and the TEJ 1 desired limit of about .0005 inch), with the expectation that future improvements in both the data reduction and the smoothing processes will decrease the gap between them.

Figures 13 and 14 illustrate the quality of the forces obtained for two example mass points from TEJ 1 using positions obtained from the JET 1 example described above, and imposing a random probable error of .003 inch. The position data were smoothed using 15 Fourier harmonics, and 7 Legendre polynomials. The results in Fig. 13 show that at early times the calculated force components approximate the exact value well for mass point No. 37 on which the force is centered, but they deteriorate markedly toward the end of the time history. For the mass point No. 1 which is located diametrically opposite mass point No. 37, the force components should be zero; Figure 14 shows that only the force component in the normal direction is well approximated, and the calculated force component in the tangential direction is quite poor. If the number of smoothing coefficients used is decreased, the calculated force components become poorer at the mass point where the force is applied, but improve at the diametrically-opposite point.

3.4.2 Data Reduction

The position accuracy obtainable by using techniques and equipment available at NAPTC was evaluated from four sets of data. The first and second sets were read from film records taken of a static ring. A quarter of the mass points (approximately 20) plus reference marks placed on a background were read in each case for a total of 19 and 7 frames per test, respectively. In each set, in order to find the relative positions of the mass points and the reference marks (the reference marks were treated in the same manner as the ring mass positions in this accuracy determination; when reducing the data to be used in TEJ 1, the reference marks are used to establish the inertial coordinate system) a reference axis for each frame was determined from the center of gravity of the points measured in each frame (in viewer coordinates). The orientation of each reference axis was determined by the average angle of all of the points relative to the viewer x-axis. The coordinates of all of the points relative to the new reference axis for each set of data were calculated and an error analysis was performed on the resulting sets of point positions, in terms of their differences from their respective mean values. The second two sets of data were obtained from film taken of actual dynamic tests, where rings were impacted by burst rotor parts. In these two cases, only the reference point positions could be used in the error analysis since the mass point positions were not static. Otherwise, the error analyses were performed exactly in the same manner as was done in the first two sets. As mentioned previously, the results obtained showed that the probable error of the measurements varied from 0.010 inch to 0.02 inch on the ring for the four tests.

In an effort to discover ways of improving the measured data, the data from the two static cases were analyzed frame-by-frame and point-by-point. These results showed a considerable variation in the PE between points. There are at least two causes for this. The first is that the film was not of consistent quality for all of the points read (due possibly to variations in lighting) and second, it was more difficult to position the reader reticule for some points than for others. Also evident was a general deterioration of accuracy as the number of frames read progressed; that is, the results became less uniform as more pictures were read. This indicates that fatigue of the operator of the film reader is an important consideration.

3.4.3 Preliminary Results from TEJ 1 Using Position Data Obtained from High-Speed Photographs

Position data read from the high-speed film record taken of NAPTC Test 49 [5] in which a single rotor blade impacted a 6061-T6 aluminum ring built to the dimensions described in Subsection 3.4.1 was transformed to inertial coordinates and used as input for TEJ 1*. The results obtained from TEJ 1 gave the calculated external-force time history of each of 72 mass points on the ring. Because of the preliminary nature of the results obtained, only the forces calculated for two mass points are presented. Figure 16 shows the calculated force versus time for the mass point which appears to coincide with the impact point on the ring (this can be seen from Fig. 15 which shows the last measured ring profile shape from Test 49). The calculated force-versus-time results obtained for a point diametrically opposite the estimated impact point is described in Fig. 17; note that the forces for this mass point should be zero.

In an effort to determine how meaningful these results are, (that is, how closely they represent the true forces applied to the ring) the position data obtained from JET 1, using the example problem described in Subsection 3.4.1 were perturbed with random numbers having a probable error of .010 in. (which is the average error calculated for the reference point positions obtained from

---

*Because the exact time between initiation (blade contact) and exposure of the first picture taken by the high-speed camera is not known, the position data used in TEJ 1 did not include the initial (static) shape of the ring. Thus, the forces acting on the ring during this time were not calculated. An experimental method for measuring this initiation time has been devised by NAPTC and once this time is known, the initial conditions of each ring tested can be better represented in future computer runs.

NAPTC Test 49). These perturbed data were then used as input in TEJ 1. The comparison between the forces obtained from using these data in TEJ 1 and the exact forces which were used to obtain the positions originally, provides an indication of how close the calculated forces obtained from Test 49 position data represent the exact forces which were caused by the blade-ring collision. Again, only the force-versus-time results for two mass points are shown; these results for the mass point at the center of the sine-shaped force applied to the ring and at the mass point diametrically opposite, are presented in Figs. 18 and 19, respectively. The exact force-time history is indicated by the dashed line for the mass point which was located at the center of the sinusoidal forcing function. The forces acting on the diametrically opposite mass should be zero. These results from TEJ 1 using position data with a PE of .010 in. show that the forces obtained have little correlation with the exact forces.

Comparing these results with the forces obtained from NAPTC Test 49 position data for the corresponding mass points (Figs. 16 and 17), the NAPTC results appear to be surprisingly smooth and "well behaved". Also, the forces acting on the non-loaded mass point are close to zero, as they should be. However, for the mass point located at the impact point (No. 27), the vertical force (F_z) is seen to be negative and the horizontal force (F_y) is seen to be positive. These two forces constitute a force vector (applied to the ring) whose direction points into the center of the ring rather than into the ring itself at this station, which is clearly impossible for a collision which occurs on the inside of the ring. Thus, most indications suggest that the forces calculated from the NAPTC Test 49 position data using TEJ 1 have little similarity with the actual forces which caused the deformation. This result is not surprising since the probable error of the position data of Test 49 is more than three times the "acceptable" level discussed in Subsection 3.4.1. Subsection 3.5, which follows, contains some suggestions which can be used to improve the above results.

3.5 Comments

As mentioned in Subsection 3.2, the PE of the position data read from the high-speed film records was found to be about .010 inch. Thus, the chosen value of allowable PE in TEJ 1 of .003 inch still falls short of what has been obtained from data reduction thus far, and further improvement in the smoothing technique is still desired. More sophisticated smoothing methods such as using spline curves for localized curve fitting have been partially investigated and there is hope that further progress in the curve smoothing process can be made.

Methods are also being sought to improve the accuracy of the measured position data. One of the most obvious ways would be to read each mass position on each frame more than once. The improvement which can be obtained is calculated as follows (Ref. 11):

$$(PE)_E = \frac{(PE)_A}{\sqrt{K}}$$

where K is the number of times each position is read

$(PE)_A$ is the probable error for any single reading

$(PE)_E$ is the effective probable error of the average of K readings

Thus, for example, by reading the positions four times, it would be possible to cut the effective error in the position data in half. Since the number of frames which must be read for each film record is as much as 50 or more, this procedure would require a great deal more effort in data reduction and, thus, would likely be used only if other more subtle methods fail.

SECTION 4

SUMMARY

A general approach toward obtaining an understanding of fragment containment/control phenomena and methods for their analysis has been outlined. Also, a computer program, called JET 1, which can be used to predict accurately whether a particular single-material ring will contain high energy rotor disk fragments if the forces resulting from the impact and other geometric and material property data are known, has been described.

In order to estimate these (as yet unknown) forces, a new method, and a preliminary computer program called TEJ 1 have been developed. This program uses position data obtained from high-speed photographs of spin-pit tests made on containment rings impacted by burst rotor parts to calculate the resultant approximate fragment-ring interaction forces.

The present position-data-accuracy obtainable requires that smoothing processes be performed before the data can be used profitably in TEJ 1. Initial smoothing methods performed on the position data have substantially improved the quality of the calculated forces from TEJ 1, but further improvements are needed. Continuing effort will be directed toward obtaining improved position data.

During the second phase of this effort, a computer program, JET 2, will be written which will predict the transient responses of hard-bonded, multilayer multimaterial, constant temperature, circular rings under arbitrary loadings. Options for describing both single and multifragment-ring impact forcing functions will be included.

In addition, it is recommended that the use of composite materials and/or structures (such as ballistic nylon, E-glass, S-glass, foam-metal combinations, etc.) for the construction of containment/deflection devices be explored.

One thing to note, for metal rings involving fragment-ring interaction is that only a small portion of the structure undergoes large straining, hence the total energy absorption, E_A, where

$$E_A = \iint_V \sigma \, d\epsilon dV$$

is relatively low.

Such may not be the case with composites if they can be made to delaminate over a large area and volume. Large amounts of energy may be absorbed in the delamination process.

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TABLE 1

SUMMARY OF INPUT PARAMETERS VARIED FOR AN ILLUSTRATIVE PARAMETRIC STUDY

Case No.	No. of Mass Points	Ring Thickness (in)	Fragment Velocity (in/sec)	Yield Stress (psi)
1	80	.1250	8,000	35,000
2	80	.1375	8,000	35,000
3	80	.1500	8,000	35,000
4	80	.2500	8,000	35,000
5	80	.1250	8,800	35,000
6	80	.1250	9,600	35,000
7	80	.1250	16,000	35,000
8	80	.1250	8,000	38,000
9	80	.1250	8,000	42,000
10	80	.1250	8,000	70,000
11	100	.1250	8,000	35,000

TABLE 2

SUMMARY OF CALCULATIONS FOR RINGS LOADED IMPULSIVELY TO TENSILE (STRUCTURAL) FRACTURE

	σ,ε Curve		Fracture Strain		*β for Initial Velocity	
Material / Run No.	Not $\dot{\varepsilon}$ Dep.	$\dot{\varepsilon}$ Dep.	Not $\dot{\varepsilon}$ Dep.	$\dot{\varepsilon}$ Dep.	Const. at 21°	Varies
Aluminum 7075-T6						
A1	x		x		x	
A2		x	x		x	
Titanium 6AL-4V						
T1	x		x		x	
T2		x	x		x	
T3	x		x			x
Steel 1020						
S1	x		x		x	
S2		x	x		x	
S3		x		x	x	

*See Fig. 11.

TABLE 3

RING PARAMETERS AND STATIC ROOM TEMPERATURE MATERIAL PROPERTIES

DATA COMMON TO ALL RINGS	
Inside Radius	7.688 in.
No. of Mass Points	60
DATA FOR RINGS OF SPECIFIC MATERIAL	
<u>1020 Steel</u>	
Density	0.000732 lb-sec^2/in^4
Thickness	0.125 in.
Centroidal Radius	7.719 in.
σ_1 = 35,000 psi	ε_1 = 0.00117 in/in
σ_2 = 60,000	ε_2 = 0.07500
σ_3 = 63,500	ε_3 = 0.20000
Failure Strain $\approx$ 27.5 per cent	
<u>7075-T6 Aluminum</u>	
Density	0.000253 lb-sec^2/in^4
Thickness	0.350 in.
Centroidal Radius	7.863 in.
σ_1 = 75,000 psi	ε_1 = 0.0075 in/in
σ_2 = 93,000	ε_2 = 0.0400
σ_3 = 137,000	ε_3 = 0.2400
Failure Strain $\approx$ 12.2 per cent	
<u>6AL-4V Titanium</u>	
Density	0.000421 lb-sec^2/in^4
Thickness	0.210 in.
Centroidal Radius	7.793 in.
σ_1 = 158,000 psi	ε_1 = 0.0090 in/in
σ_2 = 175,000	ε_2 = 0.0360
σ_3 219,000	ε_3 = 0.2360
Failure Strain $\approx$ 14.3 per cent	

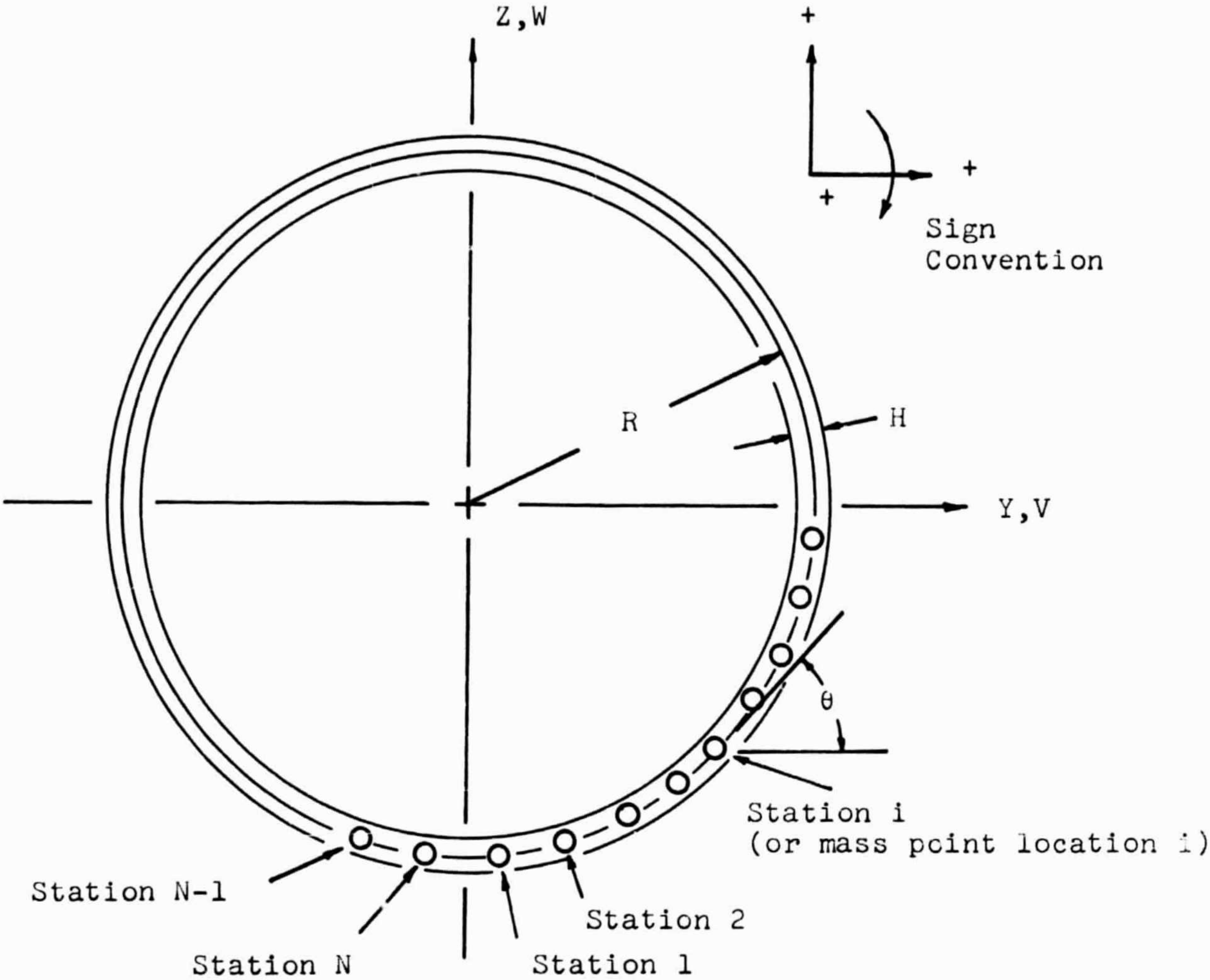


FIG. 1 FINITE-DIFFERENCE MODEL AND NOMENCLATURE FOR THE HEATED RING

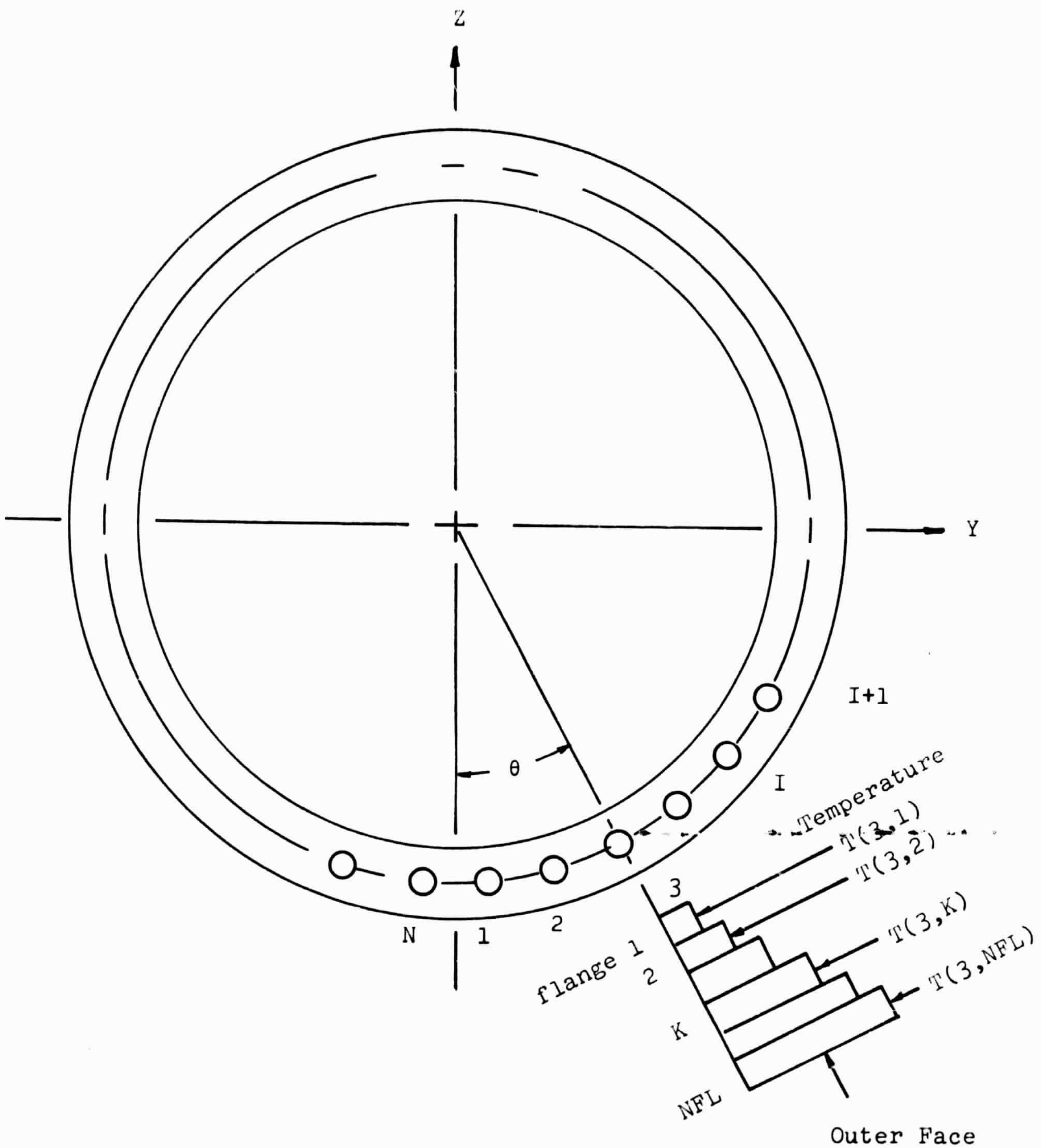
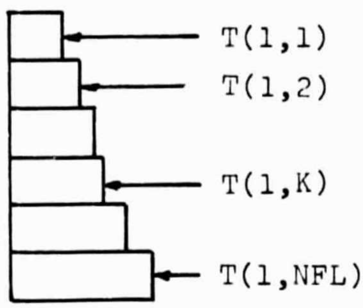


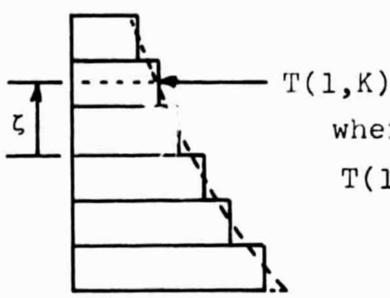
FIG. 2a SPECIFICATION OF THE RING TEMPERATURE DISTRIBUTION WITH METHOD A

(1) Radial Distribution At $\theta=0^{o}$



where T(1,K) are read-in as data

IRAID=0



where

$$T(1,K) = \frac{TZ}{H^2}\left(\zeta(K)-\frac{H}{2}\right)^2 - \frac{T1}{H}\left(\zeta(K)-\frac{H}{2}\right) + T2$$

TZ, T1 and T2 are read-in as data

IRAID=1

(2) Circumferential Distribution Of T(1,K)

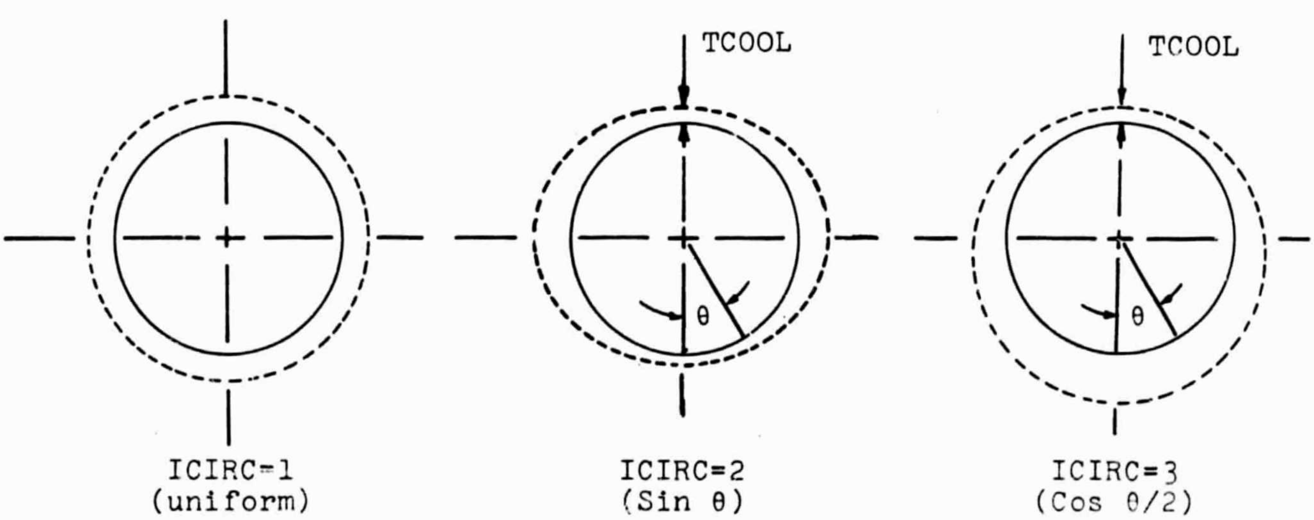


FIG. 2b SPECIFICATION OF THE RING TEMPERATURE DISTRIBUTION WITH METHOD B

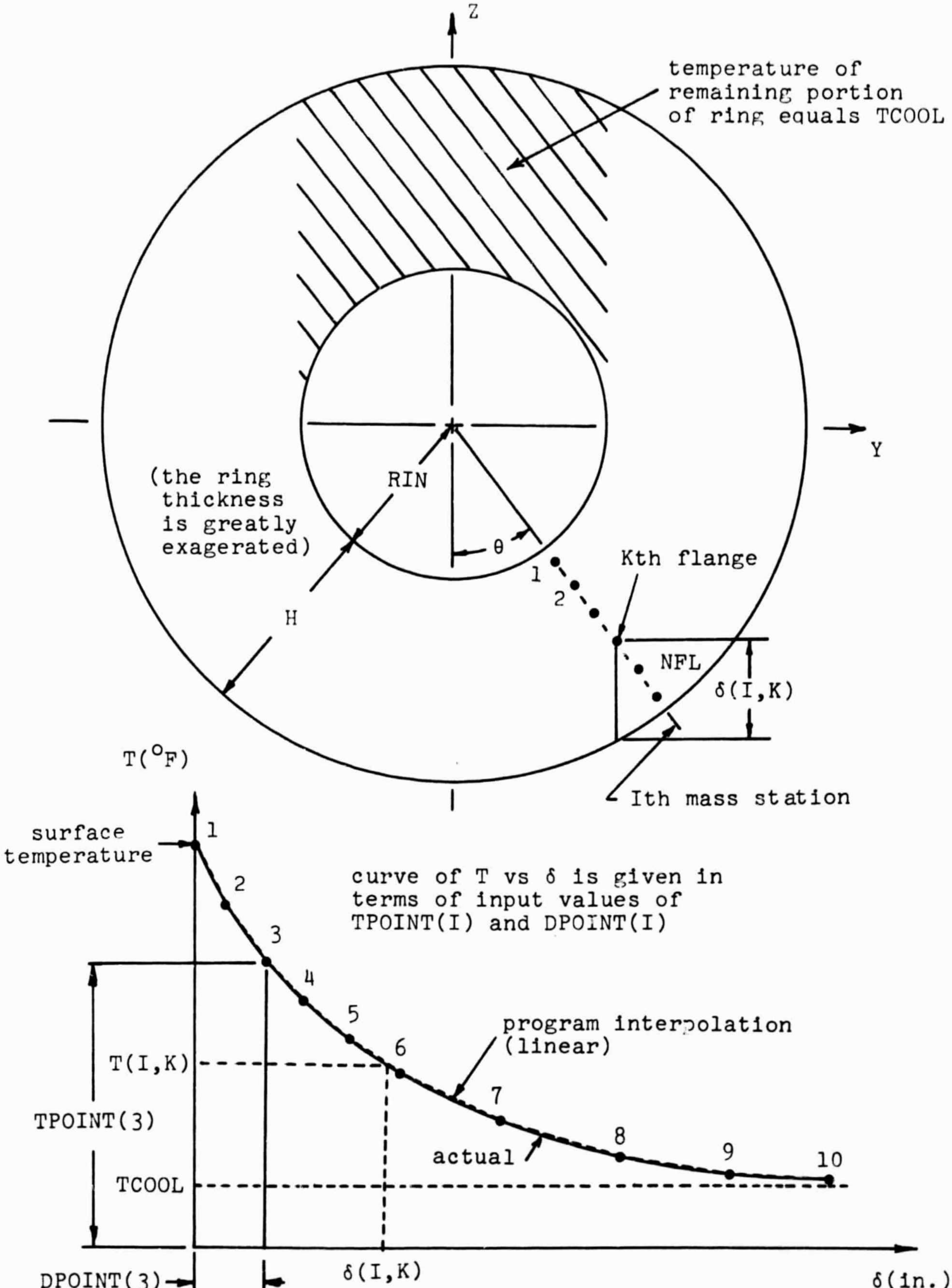
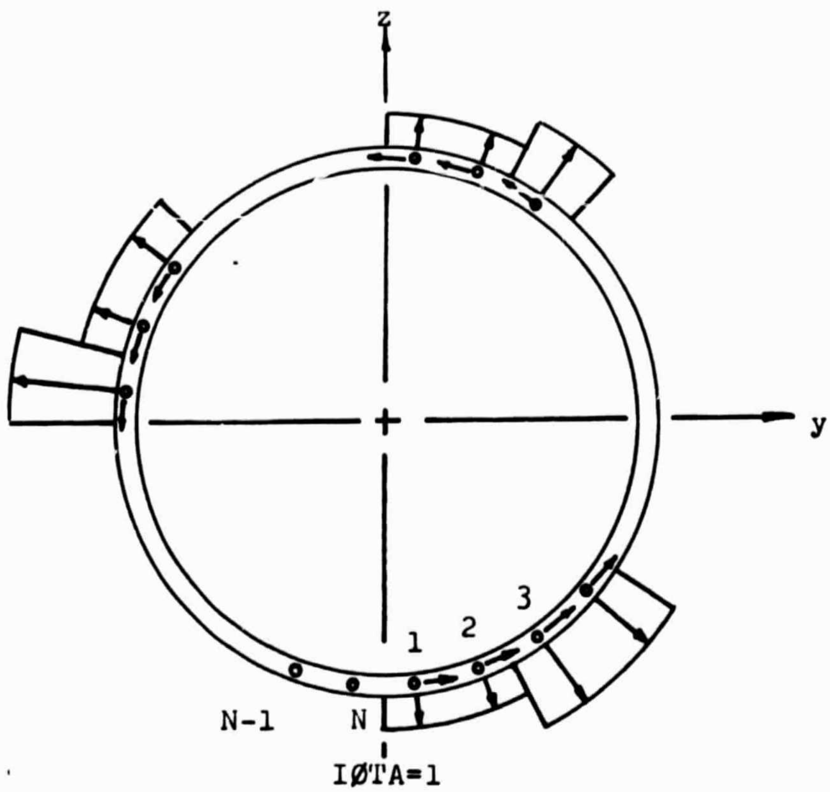
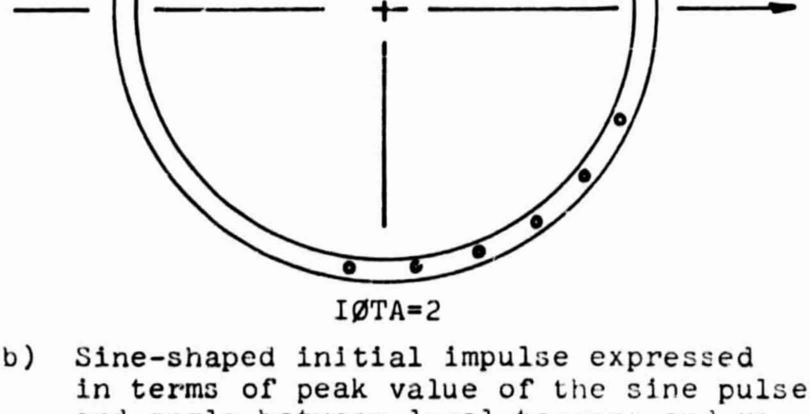


FIG. 2c SPECIFICATION OF THE RING TEMPERATURE DISTRIBUTION WITH METHOD C



a) Initial impulse expressed in terms of initial mass point tangential and radial velocities



b) Sine-shaped initial impulse expressed in terms of peak value of the sine pulse and angle between local tangent and velocity vector

FIG. 3 CIRCUMFERENTIAL DISTRIBUTION OF THE INITIAL IMPULSE CORRESPONDING TO SPECIFIC VALUES OF IOTA

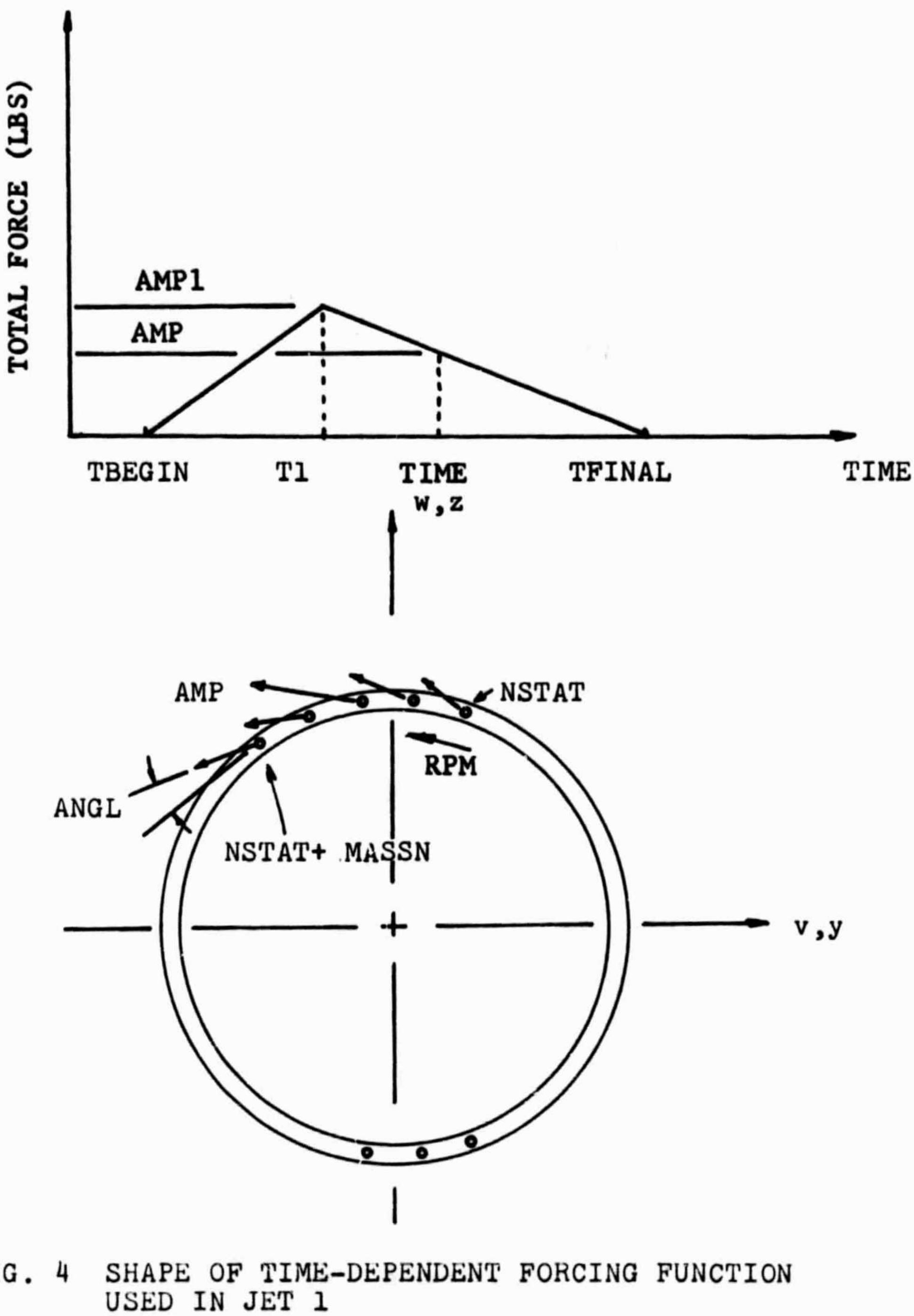


FIG. 4 SHAPE OF TIME-DEPENDENT FORCING FUNCTION USED IN JET 1

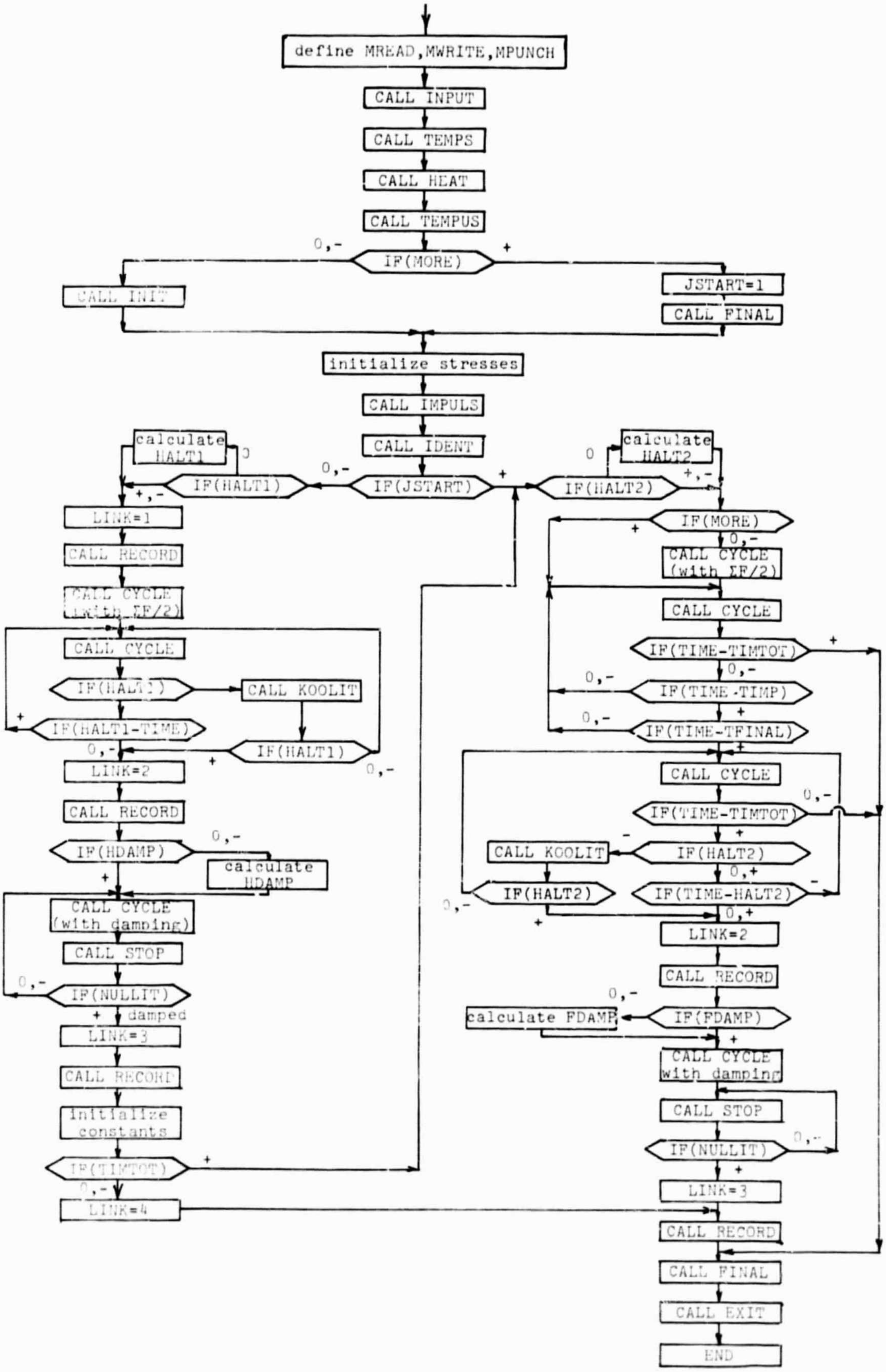


FIG. 5 FLOW CHART OF MAIN PROGRAM

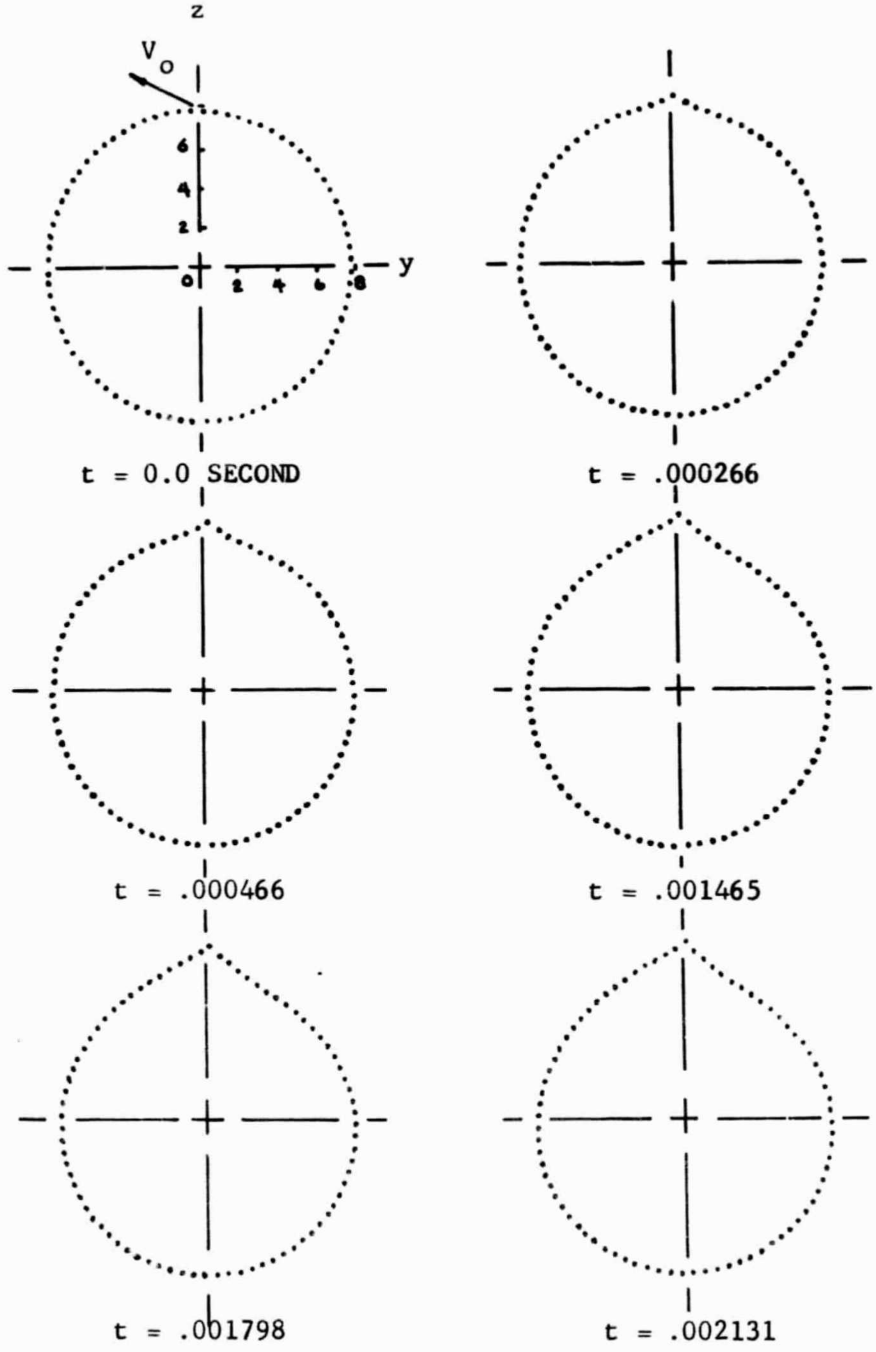


FIG. 6 RING PROFILE AT SELECTED TIMES DURING DYNAMIC RESPONSE FOR CASE 1

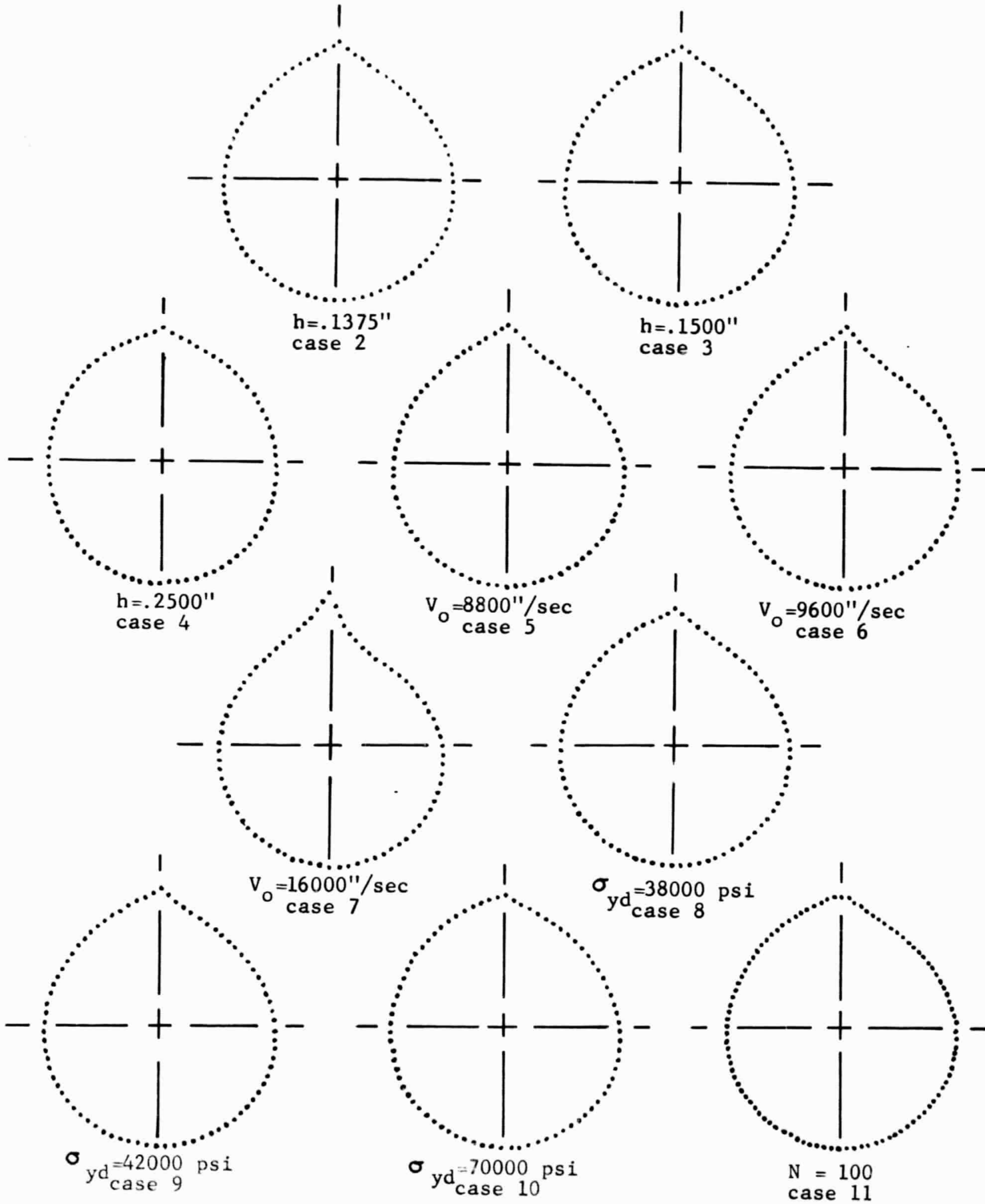


FIG. 7 RING PROFILES AT t = 0.002140 SECOND FOR CASES 2 THROUGH 11

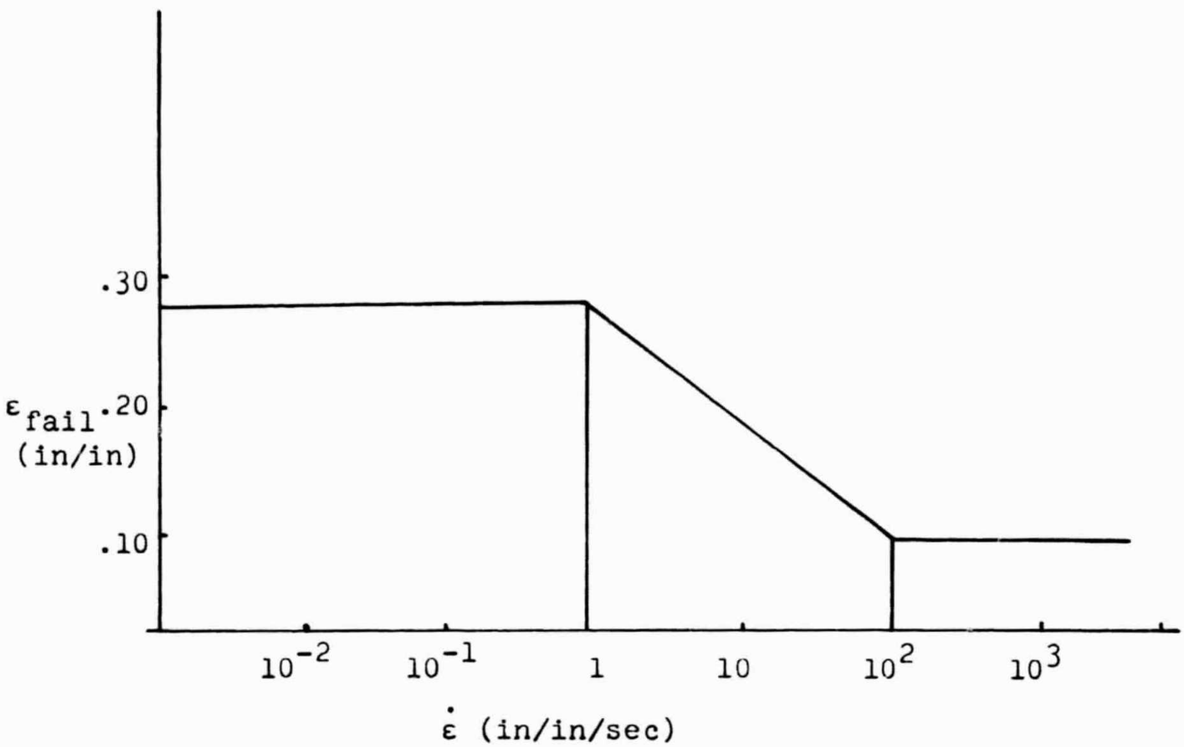


FIG. 8 TENTATIVE VARIATION OF FRACTURE STRAIN OF MILD STEEL WITH STRAIN RATE

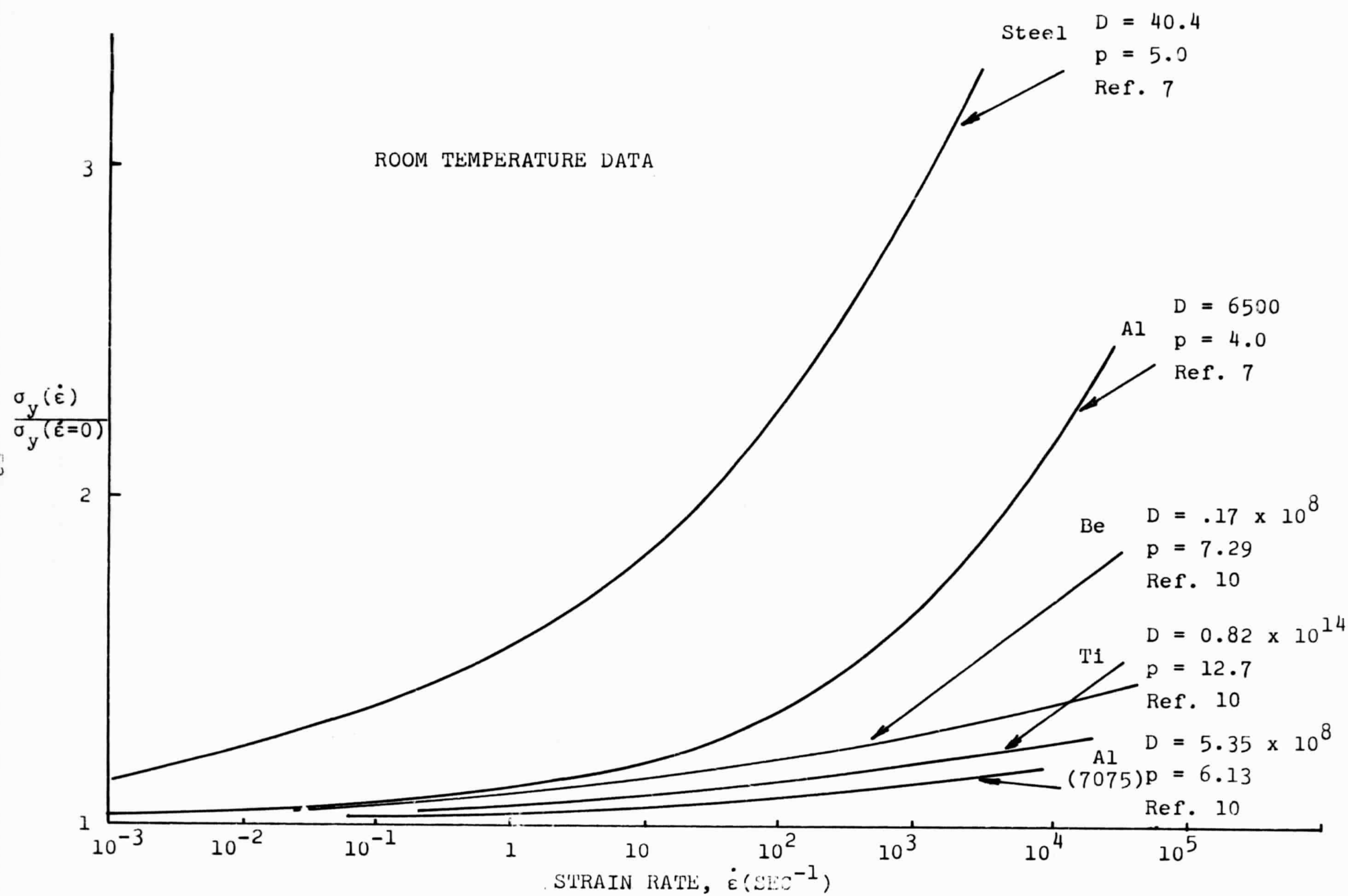


FIG. 9 RATIO OF DYNAMIC TO STATIC YIELD STRESS VS STRAIN RATE FOR VARIOUS METALS

For $\sigma_y = \sigma(1 + |\frac{\dot{\varepsilon}}{D}|^{1/p})$

MATERIAL	D	p	COMMENTS
STEEL	40.4	5.0	rough
Al-7075-T6	6500	4.0	rough and excessive
Ti-6Al-4V	$.82 \times 10^{14}$	12.69	reliable

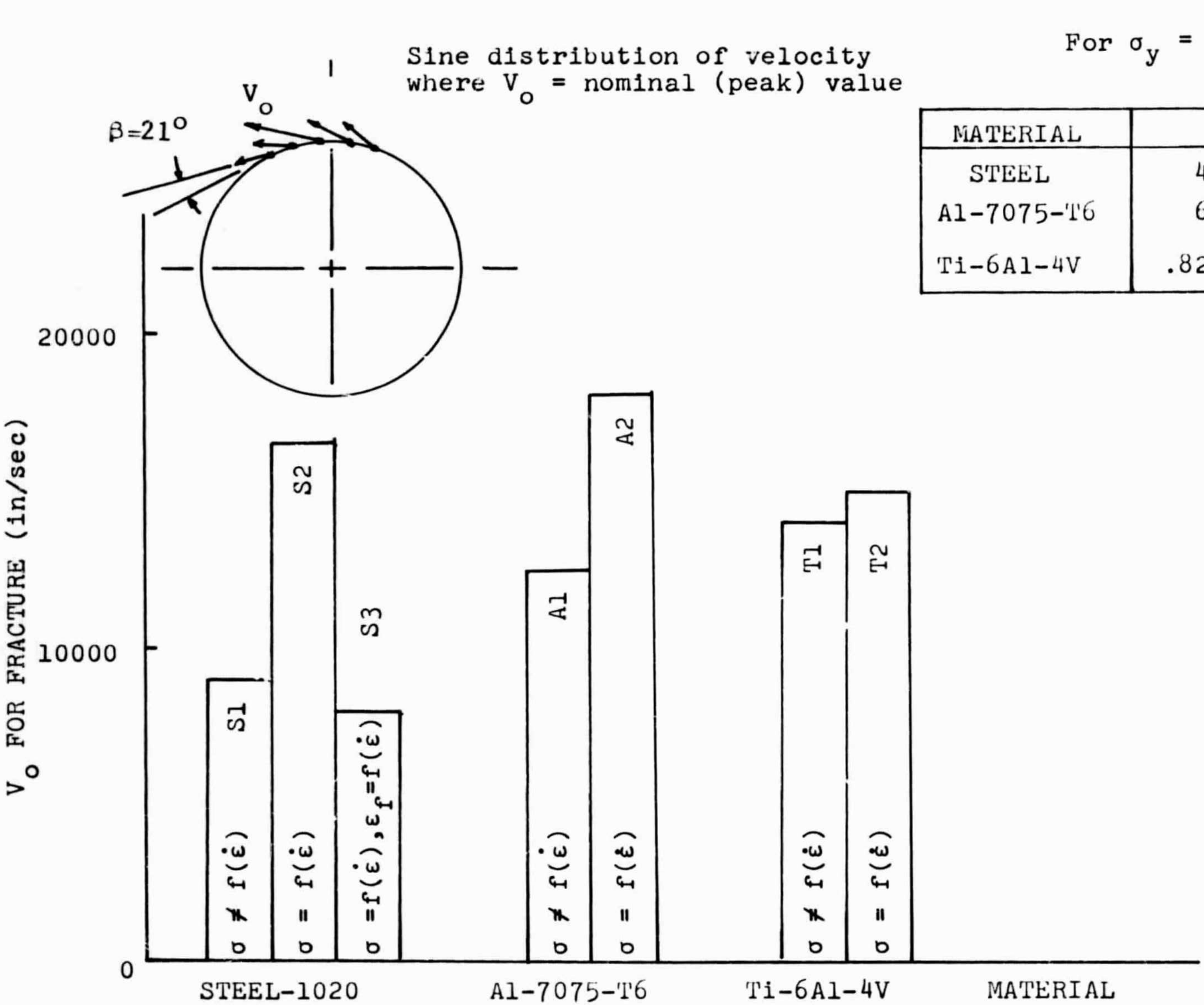


FIG. 10 RESULTS OF STUDY OF RING FAILURE DUE TO SIMULATED BLADE INTERACTION FOR RINGS OF VARIOUS MATERIALS

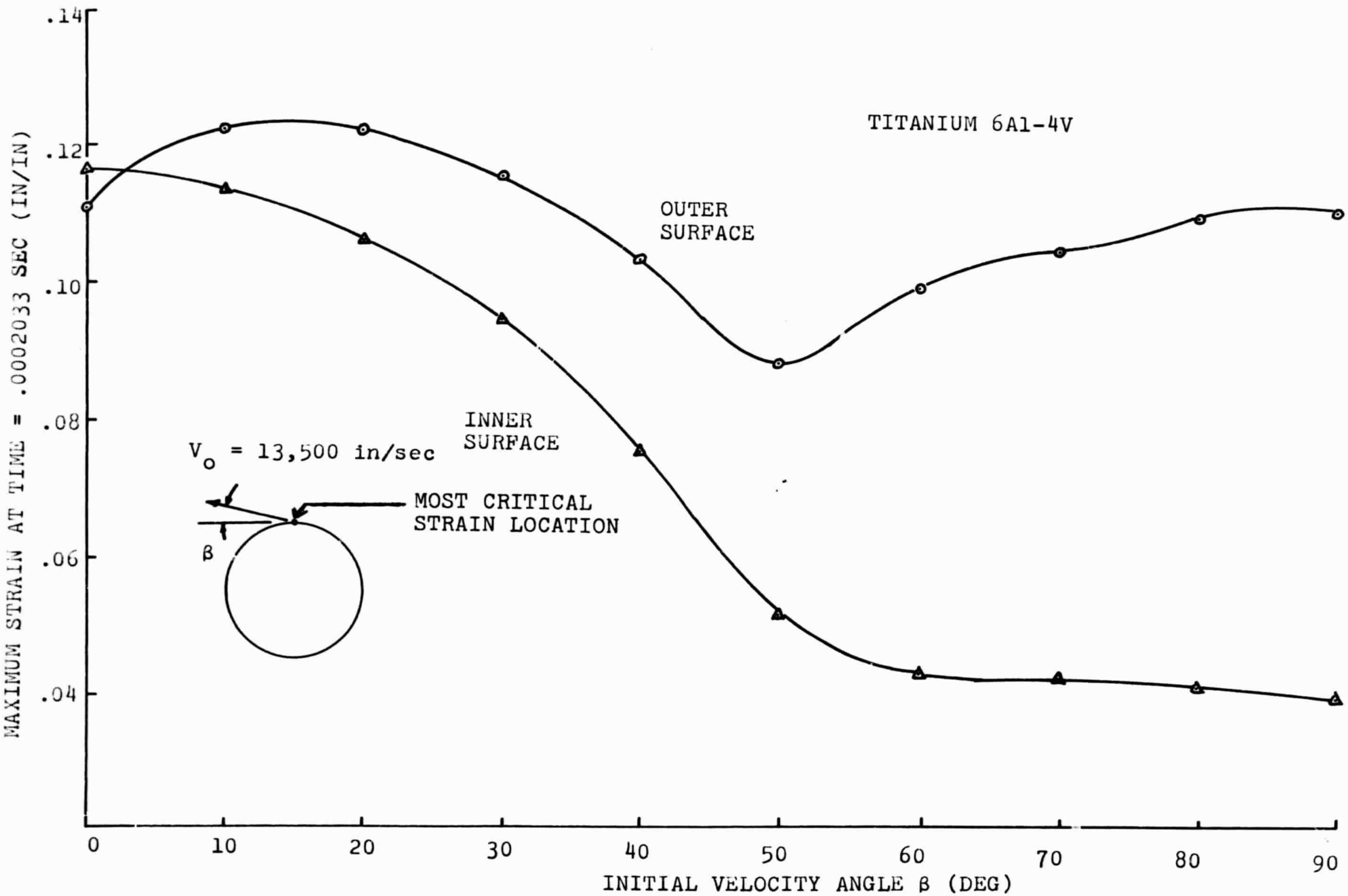


FIG. 11 EFFECTS OF β ON THE "MOST CRITICAL STRAINS" FOR IMPULSIVELY-LOADED Ti RINGS

CASE	σ_{o_y} (psi)	E (psi)	ε_{fail} (in/in)	$V_{o_{fail}}$ $^{+1000}_{-0}$ (in/sec)
1	95,000	10^7	1.00	29000
2	190,000	10^7	.51	32000
3	95,000	10^5	1.47	37000
4	47,000	10^7	2.00	33000

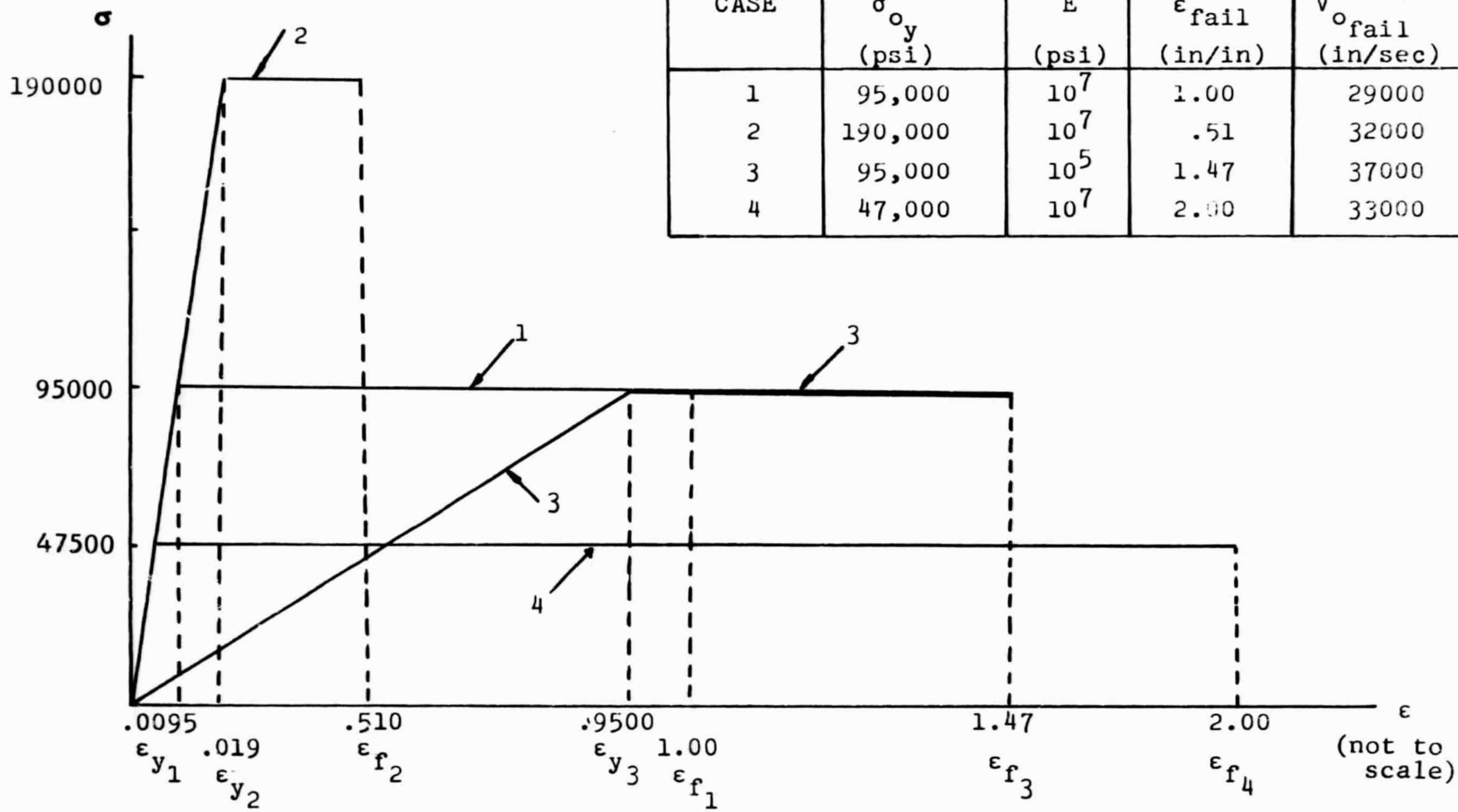


FIG. 12 VARIATION OF CRITICAL INITIAL VELOCITY V_0 TO PRODUCE INCIPIENT FRACTURE FOR MATERIALS WITH VARIOUS VALUES OF E AND σ_y BUT EQUAL VALUES OF MATERIAL "FRACTURE TOUGHNESS" (AREA UNDER σ VS ε CURVE TO FAILURE ε = CONSTANT)

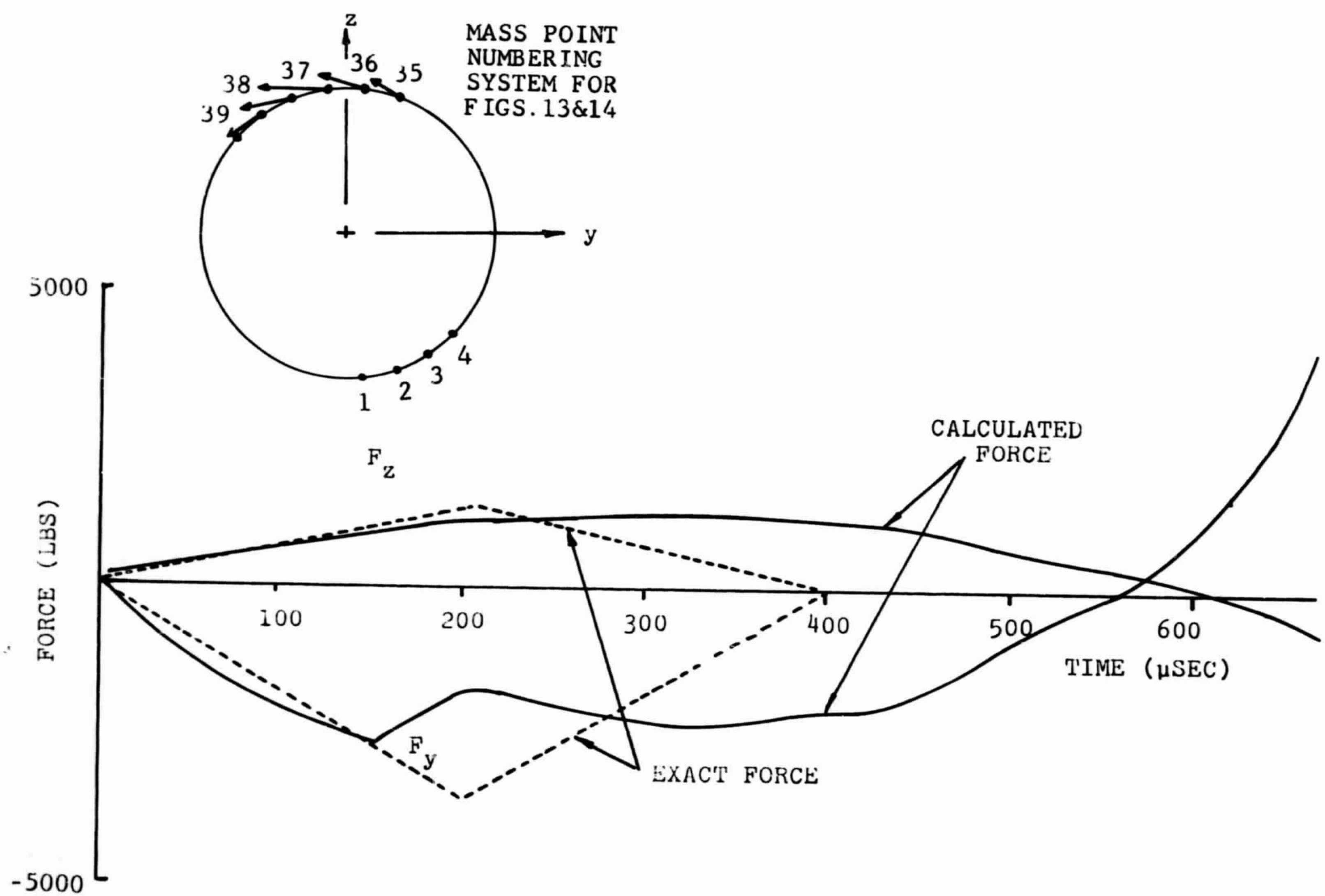


FIG. 13 CALCULATED FORCES ACTING ON MASS NO. 37 OBTAINED FROM TEJ 1 USING PERTURBED POSITION DATA FROM JET 1 WITH A PE OF .003 IN.

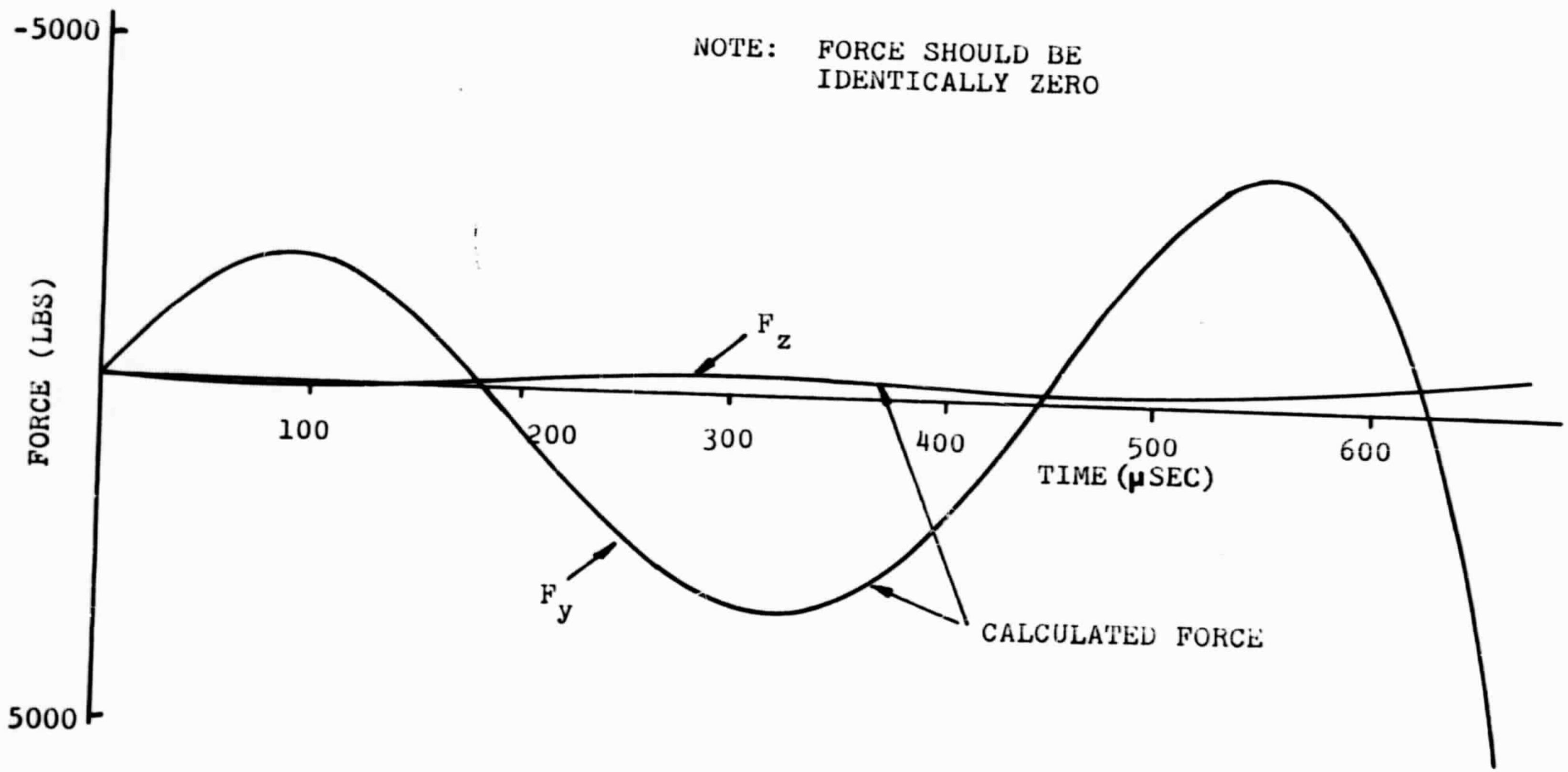


FIG. 14 CALCULATED FORCES ACTING ON MASS NO. 1 OBTAINED FROM TEJ 1 USING PERTURBED POSITION DATA FROM JET 1 WITH A PE OF .003 IN.

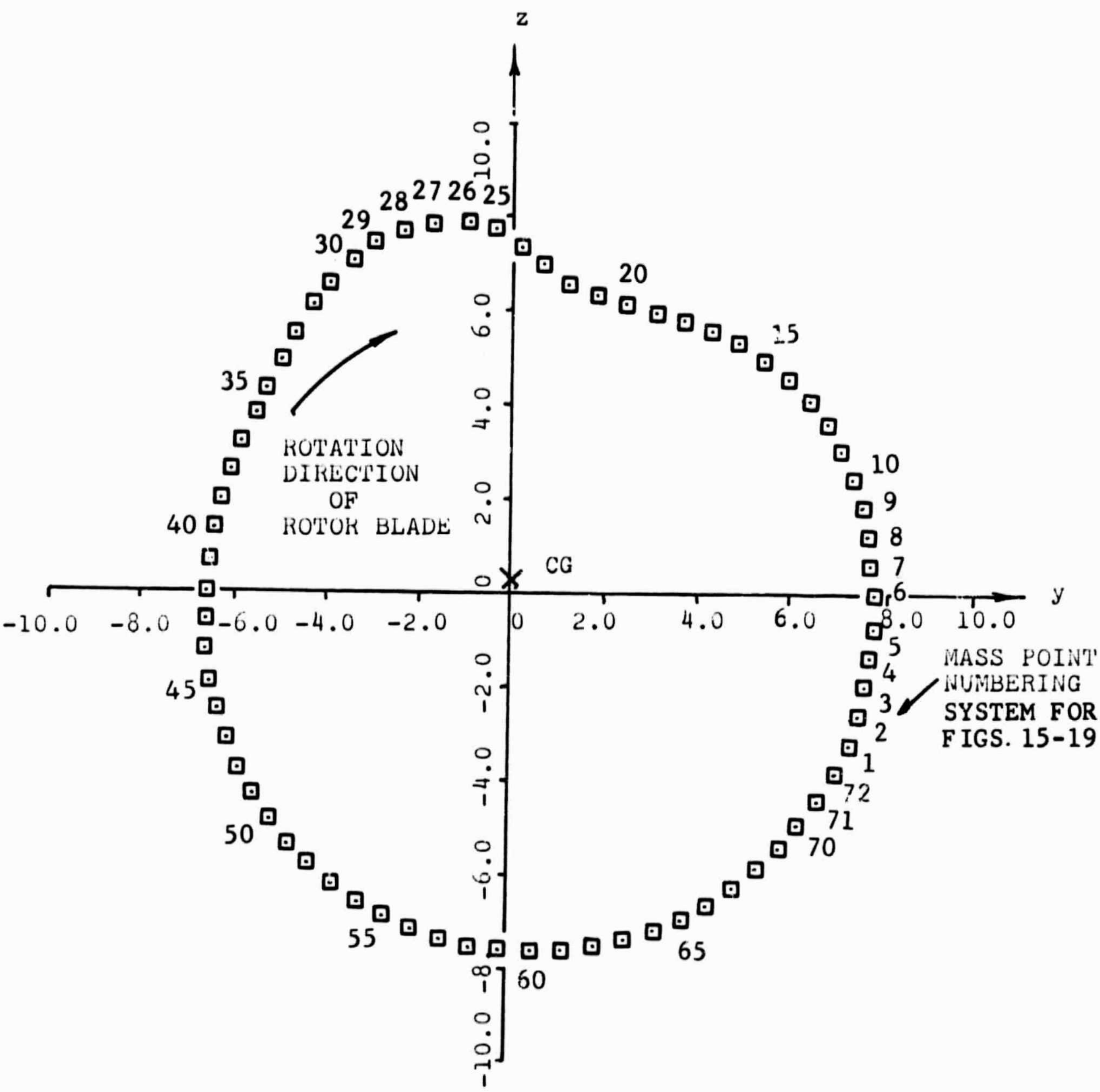


FIG. 15 RING PROFILE AT TIME 782 MICROSECONDS AFTER IMPACT MEASURED FROM HIGH-SPEED FILM RECORD OF NAPTC TESTS NO. 49

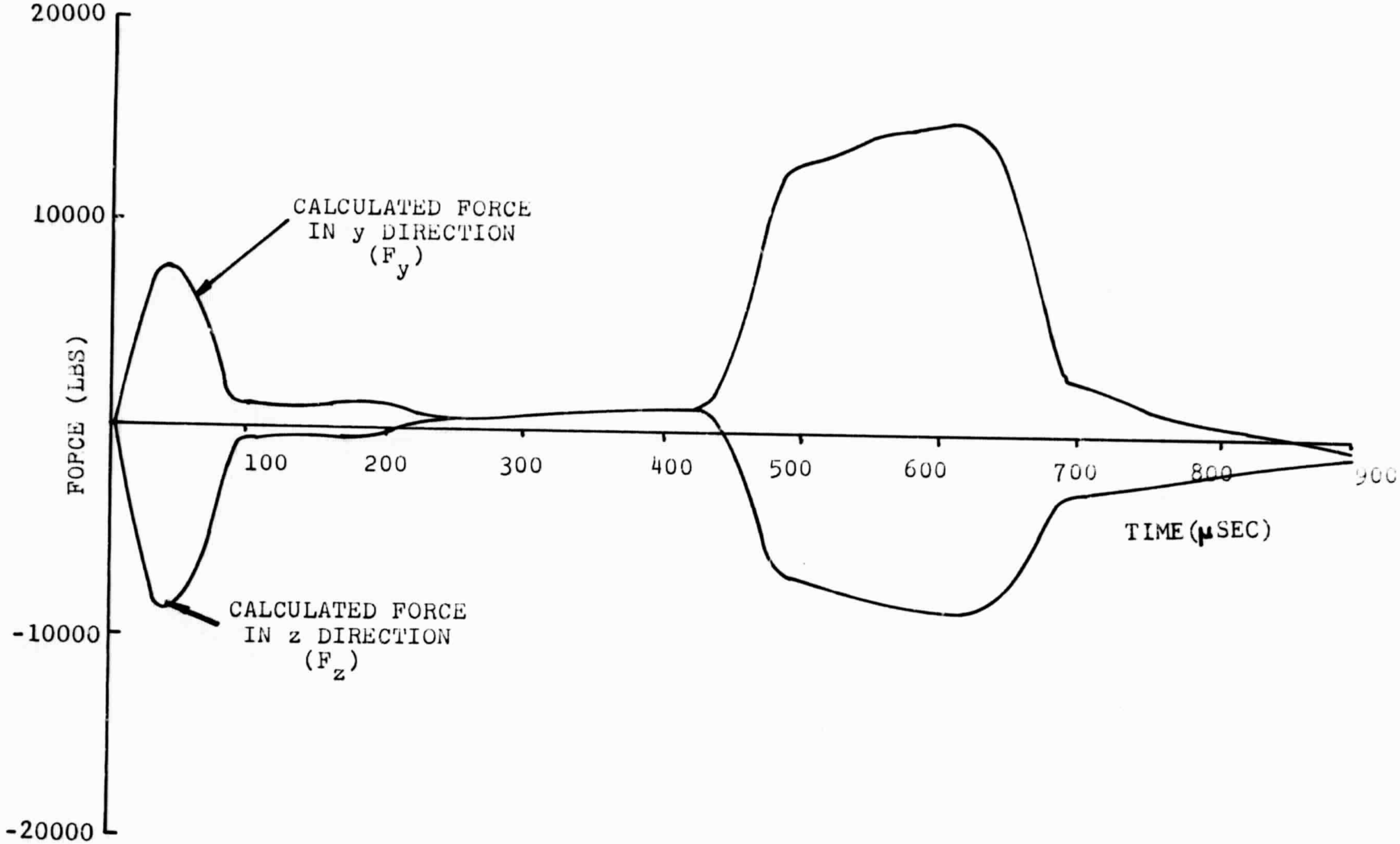


FIG. 16 CALCULATED FORCES ACTING ON MASS NO. 27 OBTAINED FROM TEJ 1 USING POSITION DATA MEASURED FROM HIGH-SPEED FILM RECORDS OF NAPTC TEST NO. 49

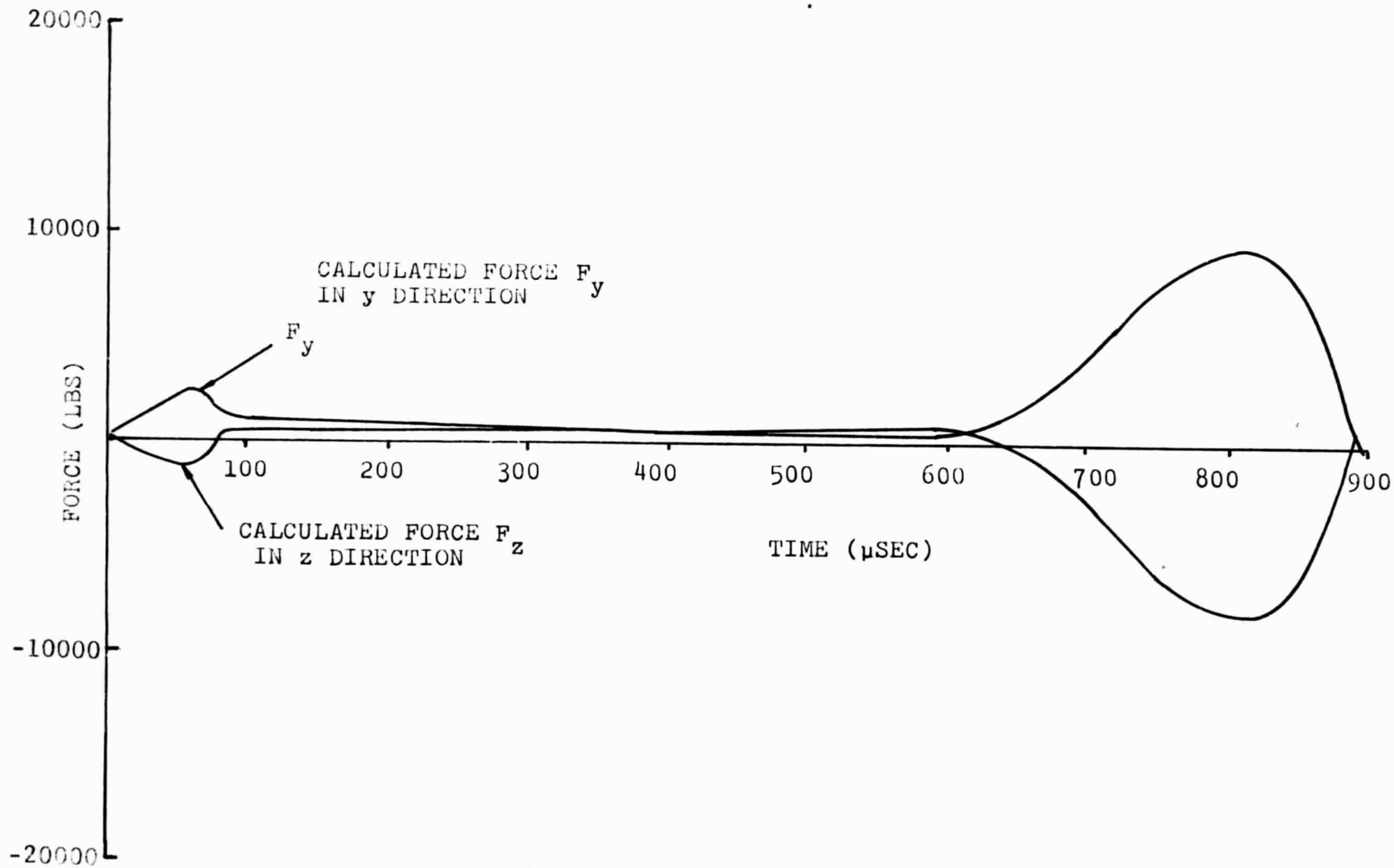


FIG. 17 CALCULATED FORCES ACTING ON MASS NO. 63 OBTAINED FROM TEJ 1 USING POSITION DATA MEASURED FROM HIGH-SPEED FILM RECORDS OF NAPTC TEST NO. 49

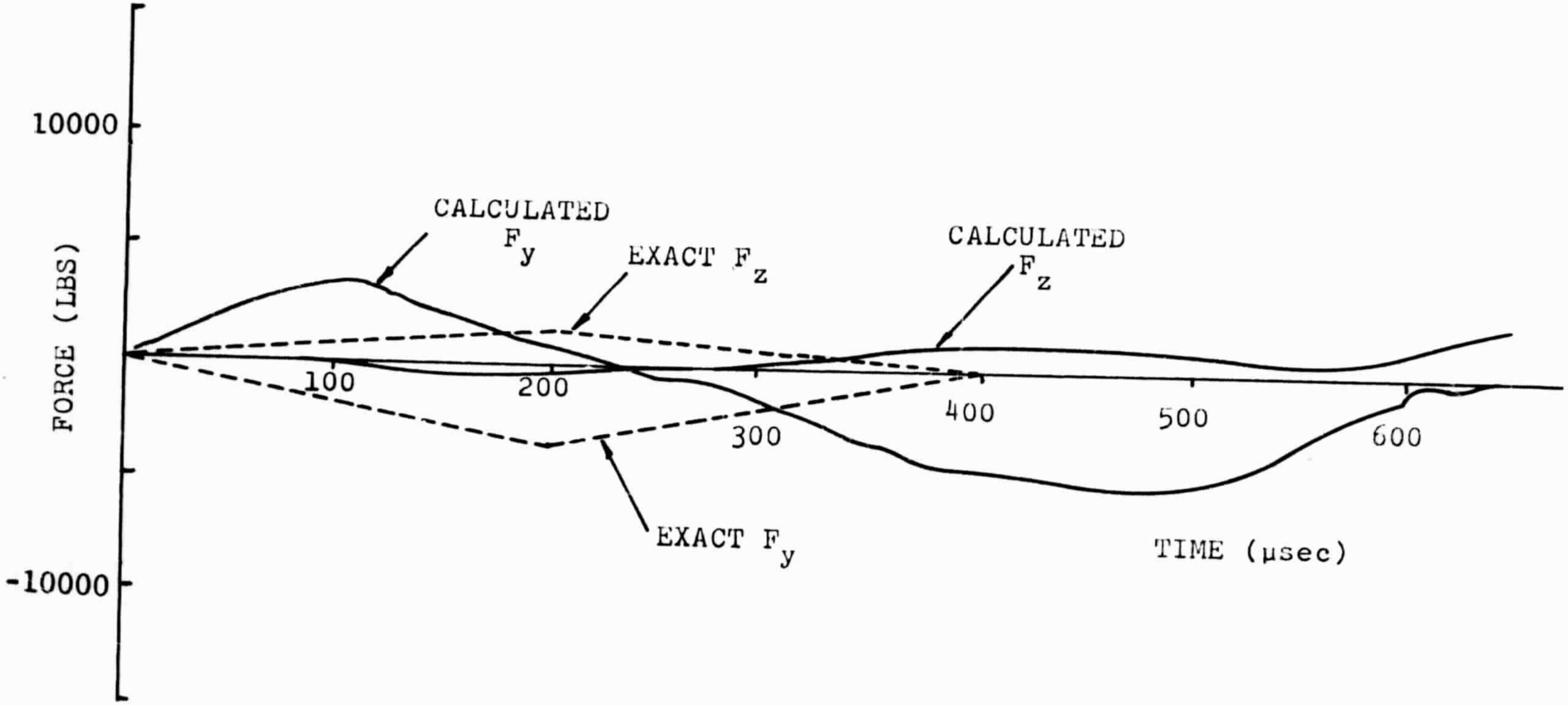


FIG. 18 CALCULATED FORCES ACTING ON MASS NO. 27 OBTAINED FROM TEJ 1 USING PERTURBED POSITION DATA FROM JET 1 WITH A PE OF .010 IN.

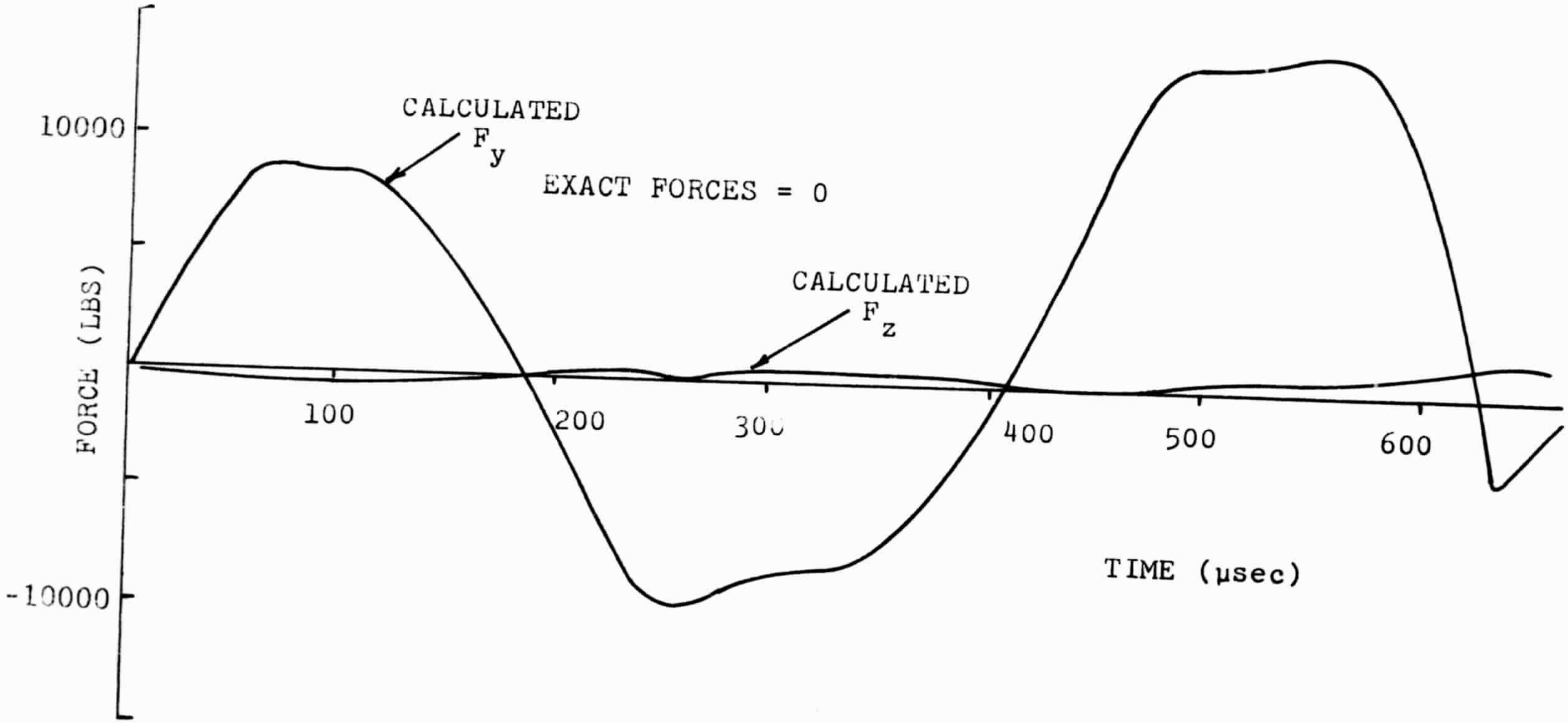


FIG. 19 CALCULATED FORCES ACTING ON MASS NO. 63 OBTAINED FROM TEJ 1 USING PERTURBED POSITION DATA FROM JET 1 WITH A PE OF .010 IN.

APPENDIX A

DERIVATION OF THE EQUATIONS OF MOTION USED IN JET 1

A.1 Introduction

The approximate numerical method used in JET 1 for the solution of transient responses of two-dimensional, single layer rings is presented in this section. The term two-dimensional is used in this section to indicate a structure which deforms in one plane only. Thus, this development can be applied to any structure such as beams, curved beams, or rings which do not deform in the direction normal to their original plane.

The present development includes the following features:

(1) A provision for including large deflections and large strains
(2) A provision for including elastic-plastic material behavior
(3) A provision for including both the tangential and transverse loadings; hence both the normal strain along the axis of the structure and the change in curvature of the structure are taken into account.

It is assumed that the thickness of the two-dimensional structure under consideration is much smaller than the general dimension of the structure; thus, in the dynamic analysis, the effects of rotary inertia and shear deformation can be neglected. In the following sections, the equations of dynamic equilibrium and the equivalent finite-difference equations are presented; the latter equations can be interpreted as representing a lumped-mass dynamic model which is also described.

In the finite difference formulation of the equilibrium equation to be used to evaluate the transient response of the structure, it will be necessary to evaluate the inplane-stress and moment resultants at specific points. Since the structure is to undergo elastic-plastic deformations, the state of stress can be conveniently calculated only at a finite number of locations through the thickness. Thus it becomes necessary to use a numerical integration method to evaluate the inplane-stress and moment resultants. Various classical numerical integration (or quadrature) methods are available for use. Integration methods such as the center-value rule or Simpson's rule, which use equally-spaced stations can be employed. Quadrature methods, such as Gaussian quadrature (which is probably the most popular and efficient of the quadrature methods used) require, in general, abscissa values at locations specified by irrational numbers, but are generally capable of supplying comparable accuracy (compared to other numerical integration methods) with half the number of terms. All of the methods evaluate the following integral by:

$$\int_{-1}^{1} f(x)\,dx \cong \sum_{j=1}^{N} W_j\, f(x_j)$$

where W_j are weighting factors whose values depend upon the location and the method (Gauss, Simpson, etc.) used, and $f(x_j)$ are the values of the function at each x_j. The inplane-stress and moment resultants to be evaluated involve integrals of the form

$$\int_{-h/2}^{h/2} g(\zeta)\,d\zeta$$

thus by setting $x = 2\zeta/h$, the integral becomes:

$$\int_{-h/2}^{h/2} g(\zeta)\, d\zeta \cong \frac{h}{2} \sum_{j=1}^{N} W_j\, g(\zeta_i)$$

A comparison can be made between the center value integration method (also called the "lumped-integration" method) and the Gaussian quadrature method by the following example tabular summary which lists the values of x_j and H_j for each case, using N = 4:

j	Center-Value Method		Gaussian Quadrature Method*	
	x_j	W_j	x_j	W_j
1	- .75	.500	-.86113 63115 94053	.34785 48451 37454
2	- .25	.500	-.33998 10435 84856	.65214 51548 62546
3	+ .25	.500	+.33998 10435 84856	.65214 51548 62546
4	+ .75	.500	+.86113 63115 94053	.34785 48451 37454

*See Ref. 14

The JET 1 program uses the central value method to evaluate the stresses because of the simplicity of evaluating x_j and W_j. However, the central-value method is not essential in this analysis; the more efficient Gaussian quadrature method could be employed by making appropriate changes in the JET 1 program.

The material behavior is assumed to be elastic-plastic with strain hardening. It will be shown that the procedure adopted in the present analysis is well suited to take into account also the effect of strain rate on the plastic behavior of typical metal materials.

A.2 Differential Equations of Equilibrium

Figure A.1 shows an element, dS, of a curved two-dimensional structure in the y-z plane in its instantaneous large-deformation state, where S is a coordinate measured along the axis of the structure. The internal forces acting on this element are the axial force N, the transverse shear force Q, and the bending moment M. The external forces acting on the element are the external forces $F_y(S)$ and $F_z(S)$ and the inertia forces due to accelerations in the y and z directions, respectively.

From the equilibrium of forces along the y-direction,

$$\left(N + \frac{\partial N}{\partial S} dS\right) \cos\left(\theta + \frac{\partial \theta}{\partial S} dS\right) - N \cos\theta$$

$$-\left(Q + \frac{\partial Q}{\partial S} dS\right) \sin\left(\theta + \frac{\partial \theta}{\partial S} dS\right) + Q \sin\theta \qquad \text{(A.1)}$$

$$+ F_y(S)\, dS - m(S)\, \ddot{v}\, dS = 0$$

where

m = mass of the structure per unit length

θ = slope of the structure = $\sin^{-1}(dz/dS)$

From Eq. A.1 the following partial differential equation of motion is obtained:

$$\frac{\partial}{\partial S}(N \cos\theta) - \frac{\partial}{\partial S}(Q \sin\theta) + F_y - m\ddot{v} = 0 \qquad \text{(A.2)}$$

Similarly from the equilibrium of forces along the z direction,

$$\frac{\partial}{\partial S}(N \sin\theta) + \frac{\partial}{\partial S}(Q \cos\theta) + F_z - m\ddot{w} = 0 \qquad \text{(A.3)}$$

By considering the moment equilibrium about an axis perpendicular to the y-z plane, the following equation is obtained

$$\left(M + \frac{\partial M}{\partial s} ds\right) - M - Q\,ds = 0 \qquad \text{(A.4)}$$

Thus the third equation of equilibrium is

$$\frac{\partial M}{\partial s} - Q = 0 \qquad \text{(A.5)}$$

A.3 Finite-Difference Equations

The differential equations of equilibrium, Eqs. A.2, A.3, and A.5, can be finite-differenced in space by substituting the following central-difference, finite-difference approximation for the partial derivatives:

$$\left(\frac{\partial f}{\partial S}\right)_i = \frac{f_{i+1} - f_{i-1}}{2\Delta S_i} + O\left[(\Delta S)^2\right] = \frac{f_{i+1/2} - f_{i-1/2}}{\Delta S_i} + O\left[\frac{(\Delta S)^2}{(2)^2}\right]$$

or, using a forward difference so that the 1/2 indices disappear

$$\left(\frac{\partial f}{\partial S}\right)_i = \frac{f_{i+1} - f_i}{\Delta S_i} + O\left[(\Delta S)\right] \qquad \text{(A.6)}$$

thus Eqs. A.2, A.3, and A.5 become respectively:

$$\frac{N_{i+1}\cos\theta_{i+1} - N_i\cos\theta_i}{\Delta S_i} - \frac{Q_{i+1}\sin\theta_{i+1} - Q_i\sin\theta_i}{\Delta S_i} \qquad \text{(A.7)}$$

$$+ (F_y)_i - (m\ddot{v})_i = 0$$

$$\frac{N_{i+1}\sin\Theta_{i+1} - N_i\sin\Theta_i}{\Delta S_i} + \frac{Q_{i+1}\cos\Theta_{i+1} - Q_i\cos\Theta_i}{\Delta S_i}$$

$$+ (F_z)_i - m_i\ddot{W}_i = 0 \tag{A.8}$$

$$\frac{M_{i+1} - M_i}{\Delta S_{i+1}} - Q_{i+1} = 0 \tag{A.9}$$

The above equations may be considered as expressing the equilibrium of an element bounded by station i and station i+1; call this element mass-element m_i. Since m_i is equal to $m\Delta s$ and remains constant even though the distance between the two neighboring stations changes because of the straining along the axis of the structure, Eqs. A.7, A.8, A.9 can be rewritten as follows:

$$N_{i+1}\cos\Theta_{i+1} - N_i\cos\Theta_i - Q_{i+1}\sin\Theta_{i+1} + Q_i\sin\Theta_i$$

$$= (F_y)_i\,\Delta S_i - m_i\ddot{V}_i = 0 \tag{A.10}$$

$$N_{i+1}\sin\Theta_{i+1} - N_i\sin\Theta_i - Q_{i+1}\cos\Theta_{i+1} + Q_i\cos\Theta_i$$

$$= (F_z)_i\,\Delta S_i - m_i\ddot{W}_i = 0 \tag{A.11}$$

$$M_{i+1} - M_i - Q_{i+1}\Delta S_{i+1} = 0 \tag{A.12}$$

It is seen that this set of equations (A.10 and A.12) can be represented by a dynamic model with lumped masses connected by weightless straight extensible bars with bending occurring only at each mass point station as shown in Fig. A.2.

By referring to this model, several quantities in this set of equations can be expressed in terms of the locations of the lumped masses v_i and w_i. For example

$$\Delta S_i = \left[(v_i - v_{i-1})^2 + (w_i - w_{i-1})^2 \right]^{1/2} \tag{A.13}$$

$$\sin\theta_i = \frac{w_i - w_{i-1}}{\Delta S_i} \tag{A.14}$$

$$\cos\theta_i = \frac{v_i - v_{i-1}}{\Delta S_i} \tag{A.15}$$

A.4 Step-by-Step Numerical Solution

The proposed procedure for solving the three finite difference equations is a step-by-step numerical procedure. At time t_j, it is assumed that the axial force N_i, the bending moment M_i, and the location of the mass points, v_i and w_i have been determined for all stations and all previous instants of time: t_{j-1}, t_{j-2}, etc. The length of each interval ΔS_i and the angle of inclination of each link θ_i can thus be evaluated using Eqs. A.13 to A.15. The transverse shear force Q_i can also be calculated using eq. A.12. If the external loads F_y and F_z at that instant of time are given, the accelerations $\ddot{v}_i$ and $\ddot{w}_i$ for all mass particles can then be evaluated using Eqs. A.10 and A.11.

The central-difference approximation is now used to represent the second derivatives of v and w with respect to time:

$$\ddot{V}_{i,j} = \frac{V_{i,j-1} - 2V_{i,j} + V_{i,j+1}}{(\Delta t)^2} \tag{A.16}$$

$$\ddot{W}_{i,j} = \frac{W_{i,j-1} - 2W_{i,j} + W_{i,j+1}}{(\Delta t)^2} \tag{A.17}$$

From these relations, the locations $v_{i,j+1}$ and $w_{i,j+1}$ of all the mass points at $t = t_{j+1}$ can be determined. Knowing the new locations of individual mass points, the increment in strain along the axis of the two-dimensional structure and the increment in curvature at each point of the structure can be determined. From this information the increments of axial force, N, and bending moment, M, may be calculated and the calculation cycle can be repeated for as many time intervals Δt as desired. These last two steps of the computation are discussed in the following section.

A.5 Strain Displacement Relations and Constitutive Relations

In expressing the change in curvature in terms of the displacements of the mass points, an approximate scheme is used. The radius of curvature at point i is assumed to be the radius of the circle which passes through the mass points at the $i-1^{st}$, i^{th}, and $i+1^{st}$ stations. The curvature which is the reciprocal of the radius of curvature is given by the following relationship:

$$\left(\frac{1}{R_{i,j}}\right)^2 = \left[16\, S_{i,j}(S_{i,j} - \Delta S_{i+1,j})(S_{i,j} - \Delta S_{i,j})(S_{i,j} - b_{i,j})\right] \left[(\Delta S_{i+1,j}\, \Delta S_{i,j}\, b_{i,j})\right]^{-2} \tag{A.18}$$

where

$$S_{ij} = \frac{1}{2}\left[\Delta S_{i+1,j} + \Delta S_{i,j} + b_{ij}\right] \tag{A.19}$$

and

$$b_{ij} = \left[\left(V_{i+1,j} - V_{i-1,j}\right)^2 + \left(W_{i+1,j} - W_{i-1,j}\right)^2\right]^{1/2} \tag{A.20}$$

The change in curvature from the initial curvature is given by

$$K_{ij} = \frac{1}{R_{ij}} - \frac{1}{(R_i)_o} \tag{A.21}$$

where $(R_i)_o$ is the radius of curvature of the undeformed structure. The axial strain for the i^{th} interval can be expressed as

$$\epsilon_{ij} = \frac{\Delta S_{ij} - (\Delta S_i)_o}{(\Delta S_i)_o} \tag{A.22}$$

where ΔS_{ij} is given by Eq. A.13 and $(\Delta S_i)_o$ is the length of the i^{th} interval at the original undeformed position.

In the present development, the cross section of the two dimensional structure is replaced by a simplified model with an even number of concentrated flanges, separated by shear webs which cannot carry normal stresses and have infinite shear rigidity (Fig. A.3). With this model, the stress and strain in the structure can be defined by the individual normal stress in the N layers, invoking the assumption that plane sections remain plane throughout the response. The distance between flanges can be determined by one of two requirements: The first requires that the elastic bending stiffness of the model be equated to that of an ideal beam. If this is the case, then the following defines the area and the distance between each flange:

$$A = bh/N$$

$$d = h/\sqrt{N^2-1} \tag{A.23}$$

where b is the width

h is the thickness

and N is the number of flanges

If, on the other hand, the model exhibits the same fully-plastic pure axial load-carrying ability, and equal fully-plastic pure moment-carrying ability as the actual structure, the following flange areas and spacing result:

$$A = bh/N$$

$$d = h/N \tag{A.24}$$

Note that as the number of flanges used to represent the cross-section increases, the two values for d coalesce.

Using the assumptions of conventional beam theory, the section originally perpendicular to the axis of the structure remains perpendicular to the deformed axis. The normal strains in the upper and lower flanges can thus be expressed in terms of the axial strain and the change in curvature. It should be noted that the axial strain ε_i refers to the change in length of the i^{th} link or the interval between the i-1 and the i^{th} station, while the change in curvature refers to that at the i^{th} station. Strictly speaking, in determining the interaction between bending moment and axial force, the axial strain and the change in curvature should be evaluated at the same station. For example, the axial strain at the i^{th} station can be obtained by the average of the strains at the two neighboring intervals, i.e.,

$$\epsilon_{i^{th}\text{station}} = \frac{\epsilon_{i+1} - \epsilon_i}{2} \tag{A.25}$$

It is believed, however, that for an analysis with a sufficiently small space mesh, the error introduced will be negligible when the calculation is made by using the strain of the i^{th} link and the change in curvature at the i^{th} station. Using N = 2 (2 flanges) to illustrate the following, the increments of strain in the upper and lower flanges are given by

$$\Delta\epsilon_{u_{i,j+1}} = \Delta\epsilon_{i,j+1} + \frac{h}{4}\Delta K_{i,j+1} \tag{A.26}$$

and

$$\Delta\epsilon_{\ell_{i,j+1}} = \Delta\epsilon_{i,j+1} - \frac{h}{4}\Delta K_{i,j+1} \tag{A.27}$$

where the upper flange thickness station is located at $\zeta = \frac{h}{4}$.

In determining the increment of normal stress in the upper and lower fibers, the following trial and correction approach is used. For example, at time t_j the upper fiber stress, $\sigma_{u_{i,j}}$ and and the incremental strain, $\Delta\varepsilon_{u_{i,j+1}}$, have been evaluated. A trial value of the fiber stress at t_{j+1} is then computed based on the elastic stress-strain relation, i.e.,

$$\left(\sigma_{u_{i,j+1}}\right)_t = \sigma_{u_{i,j}} + E\,\Delta\epsilon_{u_{i,j+1}} \tag{A.28}$$

The quantity

$$\left(\sigma_{u_{i,j+1}}\right)_t / \sigma_o$$

is then calculated and the actual value of the upper fiber stress at t_{j+1} is determined according to the following conditions:

$$(1) \text{ if } \quad -1 < \frac{\left(\sigma_{u_{i,j+1}}\right)_t}{\sigma_o} < 1 \; ; \quad \sigma_{u_{i,j+1}} = \left(\sigma_{u_{i,j+1}}\right)_t$$

$$(2) \text{ if } \quad \frac{\left(\sigma_{u_{i,j+1}}\right)_t}{\sigma_o} < 1 \; ; \quad \sigma_{u_{i,j+1}} = -\sigma_o \qquad (A.29)$$

$$(3) \text{ if } \quad \frac{\left(\sigma_{u_{i,j+1}}\right)_t}{\sigma_o} > 1 \; ; \quad \sigma_{u_{i,j+1}} = \sigma_o$$

To calculate the axial stress in the lower flange, the corresponding equations can be obtained by replacing the subscript "u" in Eqs. A.28 and A.29 by the subscript "ℓ", and by setting $\zeta = -\frac{h}{4}$.

Finally, when the normal stresses in both flanges have been determined, the axial force and bending moment can be obtained from the relations

$$N_{i,j+1} = A\left[\sigma_{u_{i,j+1}} + \sigma_{\ell_{i,j+1}}\right]$$

$$(A.30)$$

$$M_{i,j+1} = \frac{Ah}{4}\left[\sigma_{u_{i,j+1}} - \sigma_{\ell_{i,j+1}}\right]$$

The above discussion of the calculation of axial forces and bending moments is based on the very simple model having a two-flange cross section. For a more accurate analysis, the cross-section can be approximated by N lumped flanges as shown in Fig. A.3. The expressions for the axial force and the bending moment then become:

$$N_i = A \sum_{k=1}^{N} \sigma_{i,k} \tag{A.31}$$

$$M_i = Ad \sum_{k=1}^{N} \sigma_{i,k} (2k - N - 1)/2$$

As noted previously, various quadrature methods, such as Gaussian or Simpson, could be used to obtain equal accuracy with fewer terms (flange stations) required. If a quadrature method is used, there is no need to use the concept of the ideal-thickness model depicted in Fig. A.3.

A.6 Remarks Concerning Strain-Hardening and Strain-Rate Effects

In the previous discussion, the stress-strain relation is based on the assumption that the material behaves as an elastic, perfectly-plastic solid. The yield stress of the material is assumed to be unaffected by the strain rate. Engineering metals, in general, are characterized by the existence of strain-hardening in the plastic range, and the plastic behavior of some materials are highly influenced by the strain rate. In this section, brief remarks will be made concerning the modifications of the basic computing program to include the strain-rate and strain-hardening effects.

The accommodation of strain hardening behavior is conveniently done by using the characterization of the constitutive behavior described, among other places, in Ref. 7. In this method, the stress-strain curve for a strain-hardening material under uniaxial stress, as depicted in Figs. A.4a through A.4c may be approximated by straight-line segments, through the use of the mechanical sub-layer concept [15]. In that concept the material at any point is considered to consist of a number of equally-strained "sublayers" of elastic, perfectly-plastic material, each with the same elastic modulus, but with a different appropriately-selected yield stress. Thus, for example, the yield stress of each of the m sublayers would equal:

$$\begin{aligned} \sigma_{y_1} &= E\epsilon_1 \\ \sigma_{y_2} &= E\epsilon_2 \\ &\vdots \\ \sigma_{y_m} &= E\epsilon_m \end{aligned} \tag{A.32}$$

where ε_1, ε_2 --- ε_m are the strains at which each sublayer becomes perfectly plastic, and these values represent the strain values at the straight-line-segment fitting points shown in Fig. A.4c. Thus, for any value of strain, ε, it is evident that sublayers 1 and 2, for example, may be in the plastic range, while all of the remaining sublayers are in the elastic range; the stress value associated with each sublayer is defined uniquely by the strain history and the value of strain and strain-rate present. Taken collectively with weighting factors C_k (to be defined later), the stress on the stress-strain curve defined by the sequence of m + 1 straight-line segments at the given value of strain ε may be expressed as

$$\sigma = \sum_{K=1}^{m} C_K \sigma_K(\epsilon) \tag{A.33}$$

where m is the number of mechanical sublayers, and the weighting factor C_k for the K^{th} sublayer may readily be confirmed to be

$$C_K = \frac{E_K - E_{K+1}}{E} \tag{A.34}$$

where

$$E_1 = E$$
$$\vdots$$
$$E_K = \frac{(\sigma_K - \sigma_{K-1})}{(\epsilon_K - \epsilon_{K-1})} \quad (K = 2, \cdots m) \tag{A.34a}$$
$$\vdots$$
$$E_{m+1} = 0$$

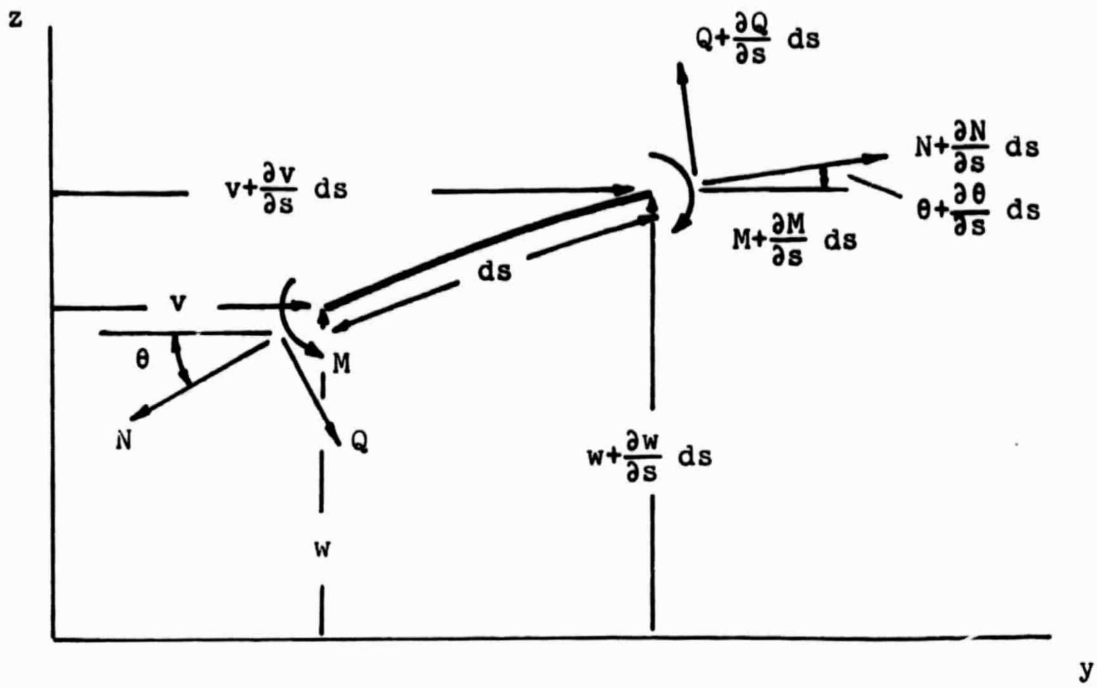
and the ε_k, σ_k define the coordinates of the piecewise linear approximation as shown in Fig. A.4c to the actual static stress-strain curve. Fig. A.4c also illustrates the method used to approximate the material behavior at elevated temperatures, where a number of static stress-strain curves, one for each of several temperature levels, can be used to obtain a stress-strain curve at a desired (intermediate) temperature by linear interpolation.

One of the simplest and most popular methods for approximating the stress-strain behavior of a simple strain-rate dependent material is taken from Ref. 12. This method pertains to an elastic, perfectly-plastic solid whose uniaxial stress-strain curve is assumed to be affected by strain rate ($\dot{\varepsilon}$) only by a quasi-steady increase in the yield stress of the material compared with that for the static case ($\dot{\varepsilon} \simeq 0$). The expression for yield stress σ_y of this material at a strain rate $\dot{\varepsilon}$ is given by the following:

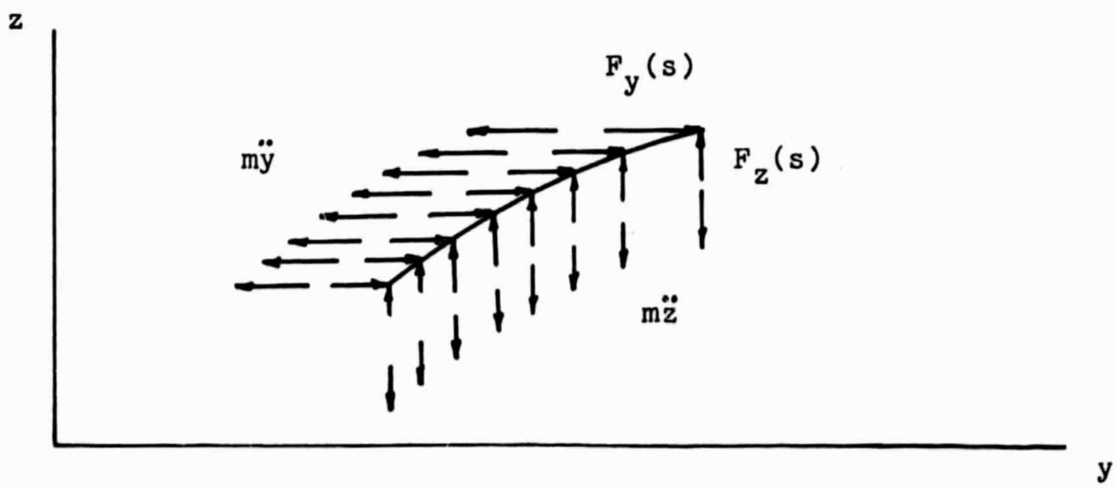
$$\sigma_y = \sigma_o \left(1 + \left|\frac{\dot{\epsilon}}{D}\right|^{1/p}\right) \tag{A.35}$$

where σ_o is the static yield stress of the material, and D and p are emirically-determined constants characteristic of the material.

Figure A.5a illustrates schematically the uniaxial stress-strain behavior for a strain-rate dependent, elastic, perfectly-plastic material whose rate dependence is described by Eq. A.35, while Fig. A.5b depicts the corresponding behavior for a strain-hardening material which is represented by the mechanical sublayer model, where each sublayer has the same values for the strain-rate constants D and p. For this special type of rate-dependent strain-hardening material, the stress-strain curve at a given strain rate $\dot{\varepsilon}$ is simply a constant magnification of the static stress-strain curves along rays emanating from the origin as shown in Fig. A.5b. However, for strain-hardening material whose strain-rate behavior is not one of simple magnification, the strain-rate behavior can often be approximated adequately by employing appropriately different values of D and p for each sublayer; the resulting behavior is illustrated in Fig. A.5c.



a) An Element, ds, of a Curved Deformed Two-Dimensional Structure



b) External and Inertial Loads Acting on the Element

FIG. A.1 SCHEMATIC OF STRUCTURAL ELEMENT

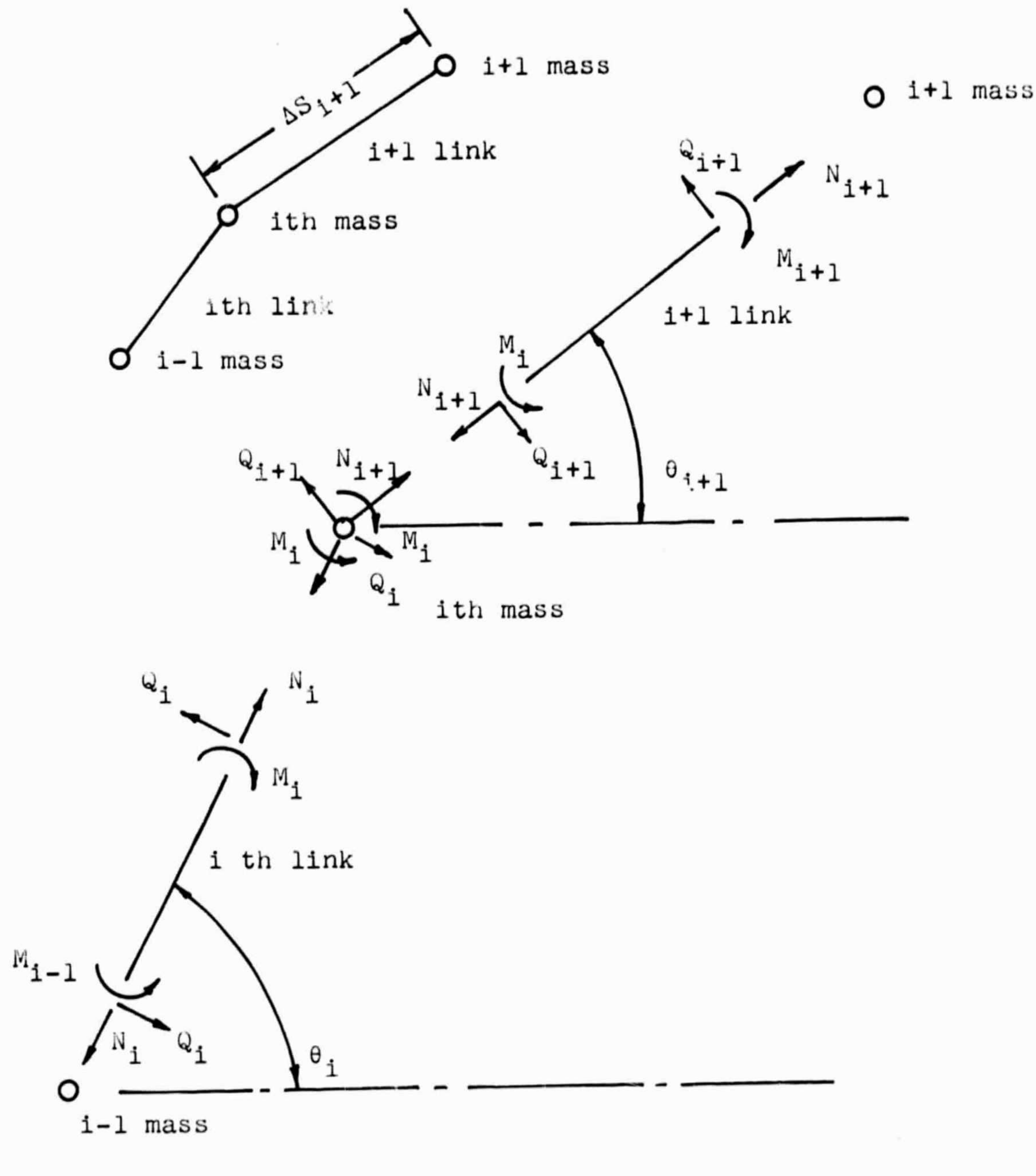


FIG. A.2 FREE BODY DIAGRAM FOR THE REPRESENTATIVE ELEMENTS OF THE LUMPED-PARAMETER MODEL

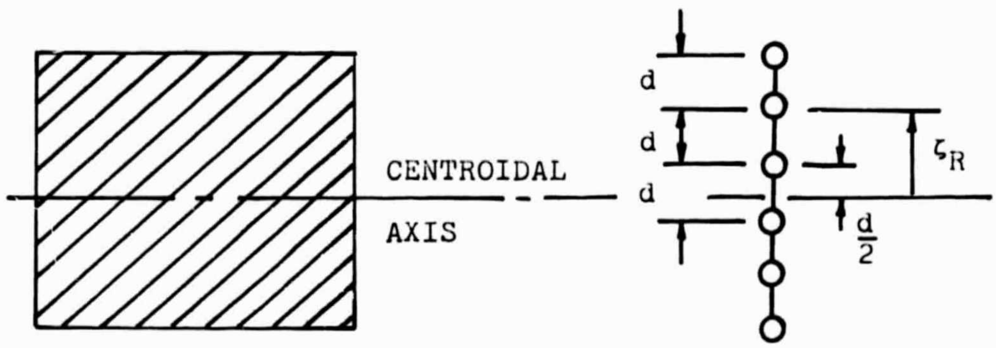


FIG. A.3 MULTI-FLANGE REPLACEMENT FOR A BEAM OF RECTANGULAR CROSS SECTION

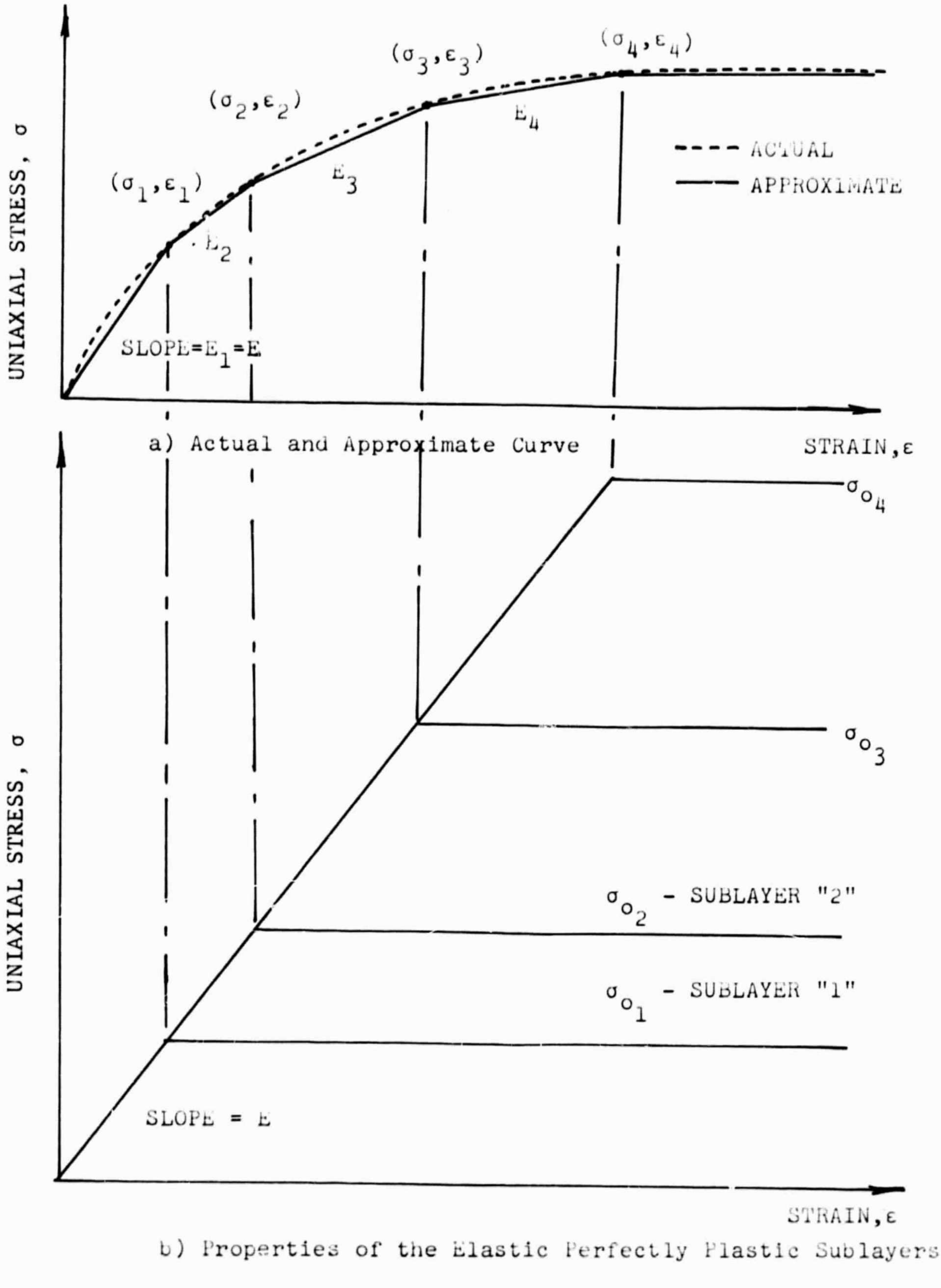
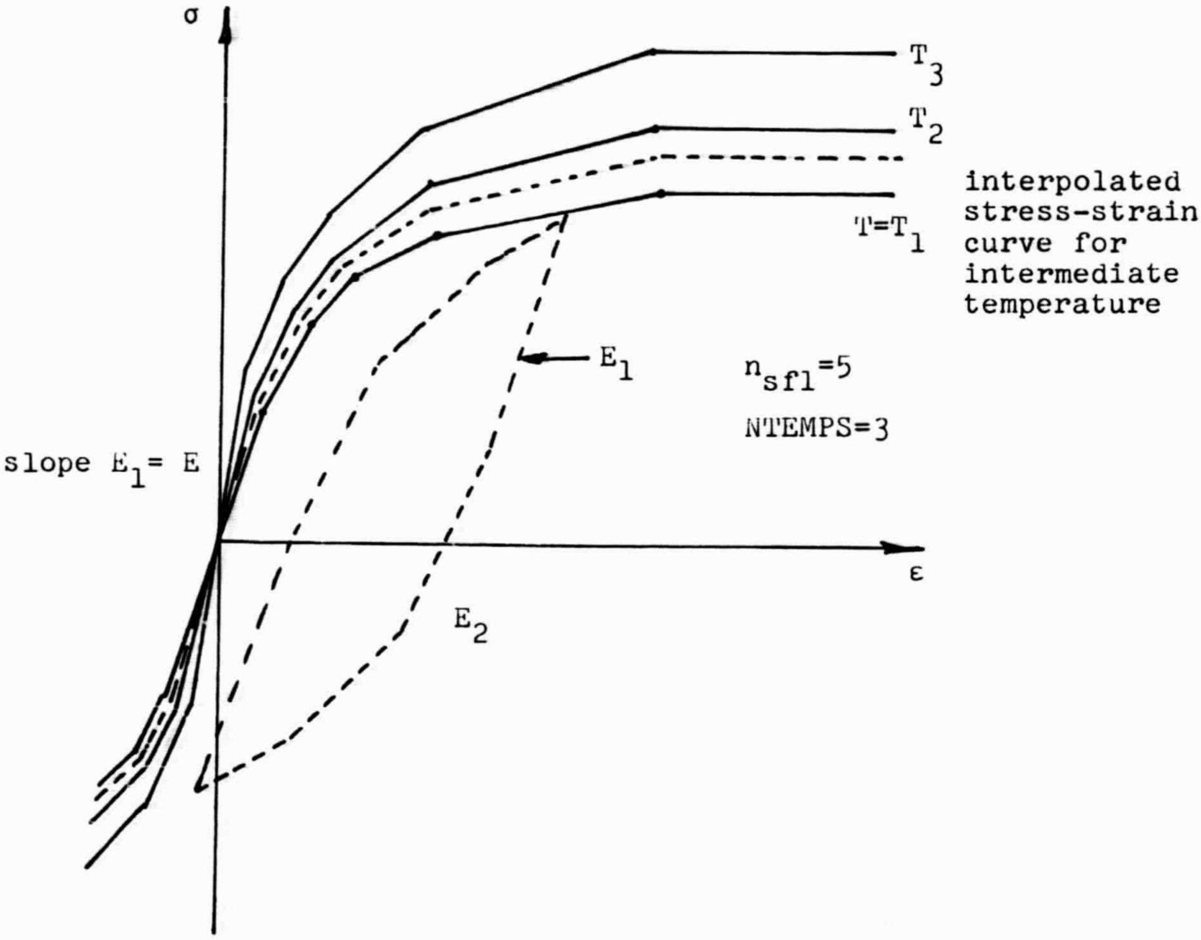
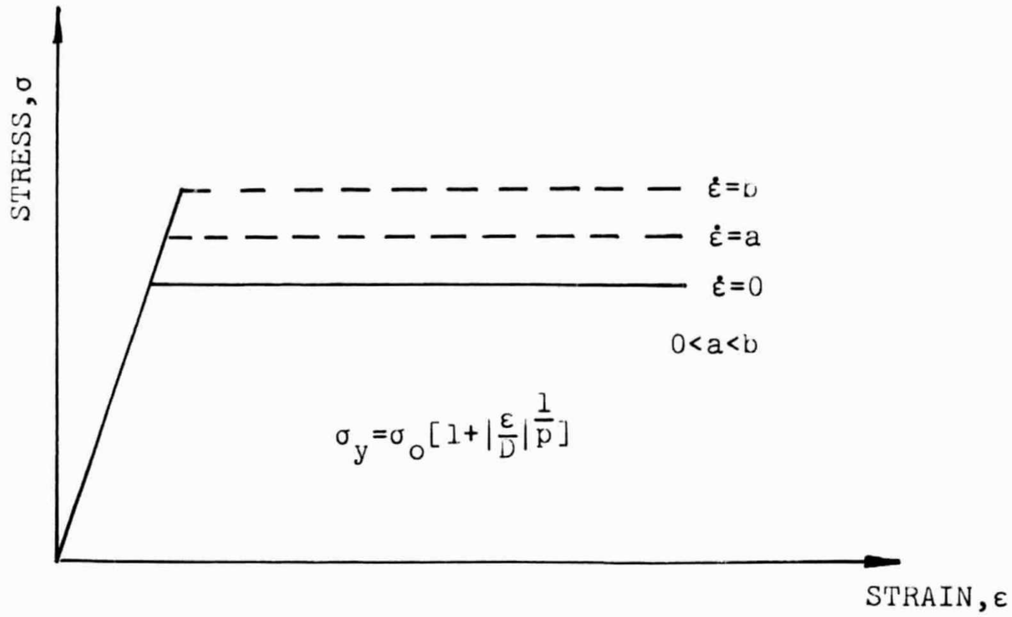


FIG. A.4 APPROXIMATION OF A UNIAXIAL STRESS-STRAIN CURVE BY THE MECHANICAL SUBLAYER MODEL

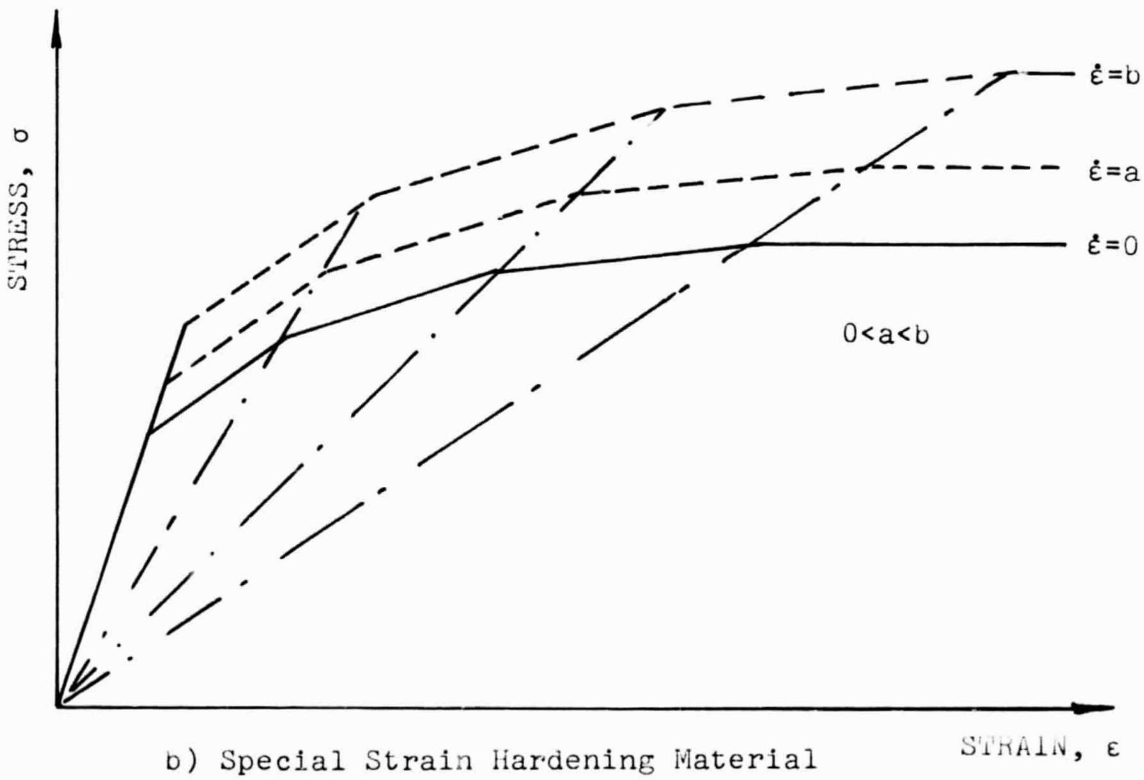


c) Static Case For 3 Temperature Levels

FIG. A.4 CONCLUDED

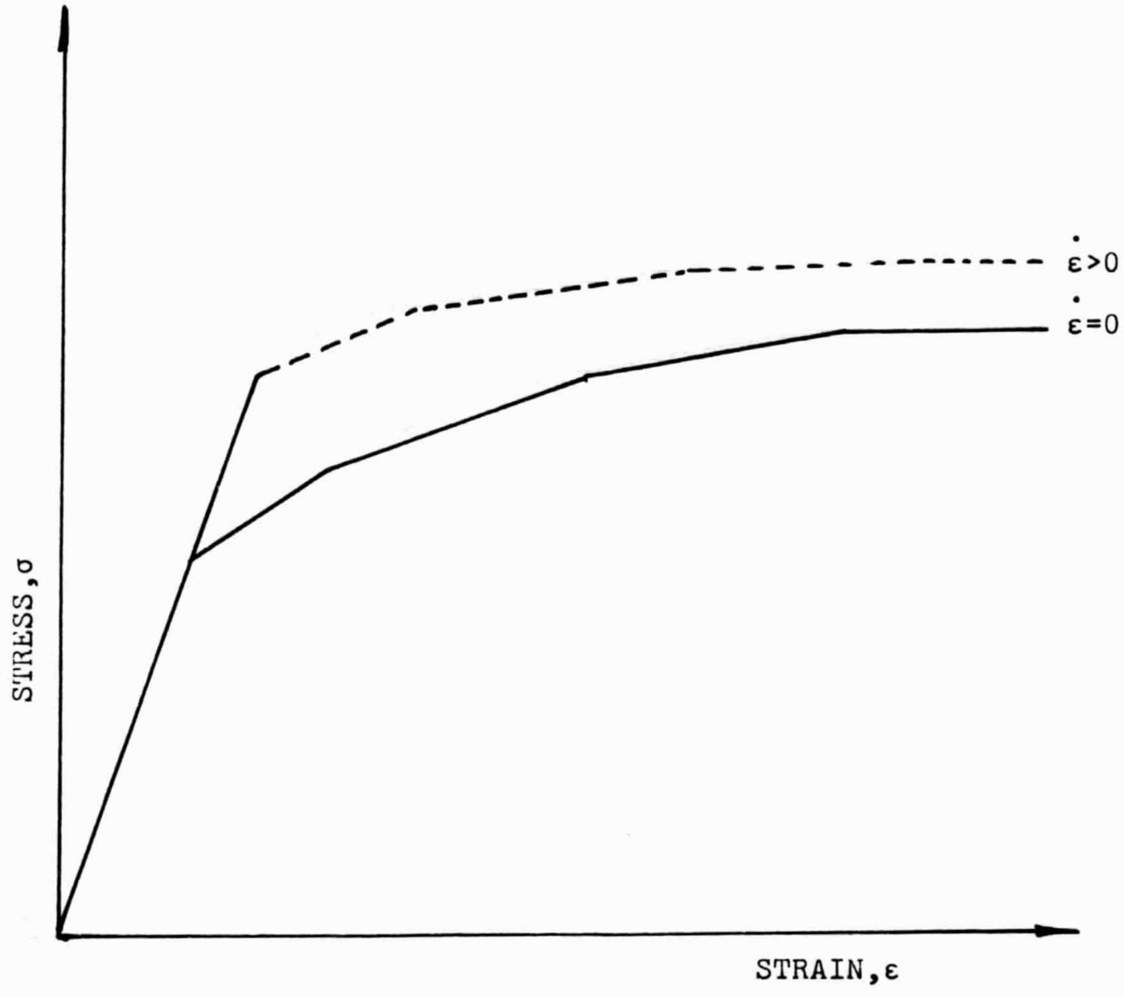


a) Elastic, Perfectly Plastic Material



b) Special Strain Hardening Material

FIG. A.5 SCHEMATIC OF STRAIN-RATE DEPENDENT UNIAXIAL STRESS-STRAIN CURVES



c) More General Strain Hardening Material

FIG. A.5 CONCLUDED

APPENDIX B

USER INSTRUCTIONS FOR THE JET 1 COMPUTER PROGRAM

B.1 Introduction

This appendix presents the detailed information required to use the JET 1 program, from the punching of the input cards to the description of a sample run with resultant output which can be utilized by the user for checking the adaptation of the program to his computing facility. Included also are instructions for using the continuation feature, a partial list and explanation of the variable names used in the program, and the FORTRAN IV listing of the JET 1 program.

B.2 Data Input Procedure

B.2.1 Input Data Required

The information needed to punch a set of data cards for a run is presented in a step-by-step manner below. The variables to be punched on the n^{th} data card are outlined in a box; to the right is the format to be used for that card; and finally, the definition and limits for each variable are given directly below. This is done for each card in turn, until all are described.

Cards 1 through 5 describe the ring geometry, the ring-model makeup, damping values to be used, and the program constants.

CARD 1 Card	Format
N,NFL,NSFL,JPRINT,JCYCLE,MORE,JSTART,JFDAMP,NTEMPS,NORATE	(10I5)

N is the number of mass points used to describe the ring (see Fig. 1). This number must be even and cannot exceed 100.

NFL is the number of flanges used to specify the cross section of the ring. The ring's thickness-wise temperature distribution is also described by assigning a temperature at each flange. NFL must be even and cannot exceed 10.

NSFL equals the number of subflanges in the strain-hardening model for the ring material, and equals the number of coordinate pairs (σ_1,ϵ_1) defining the polygonal approximation of the stress-strain diagram (see A.4a in Appendix A); NSFL must never exceed five.

JPRINT is the cycle number (for both artificial and real time) at which regular printing is to begin.

JCYCLE is the number of program cycles between regular printout. (i.e., print every JCYCLE cycles).

MORE signifies that the run is a continuation run if it equals 1. If the run is not a continuation run, set MORE = 0 (see Subsection B.4 for more complete information).

JSTART equals 0 tells the program that the initial dynamic response resulting from an imposed initial thermal stress distribution is to be damped out before real time begins and external forces are applied. If no initial damping is needed (as in the case when the ring is unheated) or desired, set JSTART = 1.

JFDAMP is the maximum number of program cycles of artificial time allowed after damping of the elastic motion has begun (JFDAMP is the total number of cycles allowed, but it is tested only after plasticity is completed). If computer time is not limited, set JFDAMP equal to 9999.

NTEMPS is the number of temperature levels at which material properties are given in data cards 13 through 16. NTEMPS must equal at least 1, and cannot be greater than 5. If NTEMPS = 1 (when the ring is at a constant temperature level) then Cards 6 through 9 and 11 must be left out.

NORATE tells the program there are no strain-rate effects if it equals 0. If there are to be strain-rate effects, set NORATE = 1.

CARD 2

	Card	Format
	R, B, H, RHO	4E15.6

R is the radius of the ring to the centroidal axis of the cross section in inches

B is the width of the ring in inches

H is the thickness of the ring in inches

RHO is the mass density of the ring material (lb-sec^2/in^4)

CARD 3

	Card	Format
	DELTAT, HALT1, HALT2, TIMP	4E15.6

DELTAT is the time interval per cycle to be used in the running of the program. As noted in Ref. 7, DELTAT cannot be chosen arbitrarily, but is subject to the following stability criterion:
DELTAT should be chosen so that it is slightly less (about 5%) than the smaller of the following two time increments (ΔT):

$$\Delta T_{Long} = \frac{\Delta S}{\sqrt{\frac{1}{NFL}(E_1+E_2+ \text{----} +E_{NFL})_{MAX}}} \tag{B1}$$

$$\Delta T_{Lat} = \frac{1/2\ (\Delta S)^2}{\sqrt{\frac{1}{\rho H}(E_1 I_1+E_2 I_2+ \text{----} +E_{NFL} I_{NFL})_{MAX}}} \tag{B2}$$

where ΔT_{Long} and ΔT_{Lat} are the critical time increments based on the wave equation and the lateral bending equation, respectively.

In general, different ΔT's will be calculated at each mass point location unless the temperature distribution is uniform around the circumference of the ring. The correct value of the critical time increment is the minimum value encountered on the ring. Thus, the maximum value of effective Young's modulus is used to calculate the critical time increments ΔT_{Long} and ΔT_{Lat}. Note that ΔS is the link length, $E_K = \sigma_{1,K} / \epsilon_{1,k}$ at each flange, ρ and H are the density and thickness of the ring, respectively, and I is the area moment of inertia of each flange about the centroidal axis of the ring's cross section divided by the ring-width B. The program will compute both ΔT_{Long} and ΔT_{Lat} and choose an appropriate value for ΔT, if the value for DELTAT is set equal to zero in Card 3:*

HALT1 is the time in seconds at which it is estimated that all plastic work will have been completed, and damping can begin in the "artificial" time portion (JSTART = 0) of the program.

If HALT1 is set equal to zero, a value for HALT1 will be calculated by the program based on the value of the period of the first mode of the ring. The time thus calculated tends to be quite conservative (longer than required). If HALT1 is set equal to - 1, the program will test the ring separation and start damping the ring motion when the ring's first-mode response has gone through a minimum and a maximum value of the ring separation. (Experience has shown that in most cases, all appreciable plastic work has been completed by the time the ring has undergone one cycle of maximum and minimum separation).

---

*The ΔT thus chosen by the program is printed out in the initial information printout of the output.

HALT2 applies to the real time portion (JSTART = 1) of the program, and it is the time in seconds required <u>after externally-applied forces have stopped</u> for plastic work to be completed (the amount required is added to TFINAL in the program). HALT2 can be set equal to 0 or - 1, and the program will calculate HALT2, and test for the end of plasticity, respectively, as with HALT1. If no damping is desired, make HALT2 very large (e.g. 1.00)

TIMP is the value of real time at which the impulsive load is applied to the ring. In most practical cases, TIMP will equal 0.0 seconds. However, in cases where the dynamic response resulting from the initial thermal stress is not damped out, it may become desirable to apply the impulsive load at some time greater than zero.

The following card describes the time-varying triangularly shaped forcing function.

<u>CARD 4</u>

Card	Format
TBEGIN, TFINAL, AMP1,T1	4E15.6

TBEGIN, TFINAL are the times (in seconds) which define the beginning and the end, respectively, of the complete triangular forcing function; i.e., the complete forcing function starts at TBEGIN and ends at TFINAL. If there is to be no forcing function during the run, set <u>both</u> TBEGIN and TFINAL equal to zero and set AMP1 and T1 also equal to zero.

AMP1 is the maximum (peak) value of the triangular shaped forcing function in pounds

T1 is the time at which the peak of the triangular shaped forcing function occurs. (See Fig. 4).

CARD 5

Card	Format
HDAMP, FDAMP, TCOOL, TIMTOT	4E15.6

HDAMP
FDAMP are the values of the damping constant to be used for damping the ring dynamic response in the artificial and real time portions of the program, respectively. Care must be taken not to make the value of damping greater than the minimum critical value of the ring based on the minimum "effective" bending stiffness of the ring's cross section (see Subsection 2.2.2.4). The program will calculate a correct value for damping in each case, if the respective input value is made equal to zero. The value thus calculated is printed out upon completion of the damping of the dynamic response. FDAMP is not used if there is to be no damping in the real portion of the run.

TCOOL is the assumed overall temperature of the ring before the temperature distribution is applied. The difference between this temperature and the imposed temperature distribution is used to calculate the initial thermal stresses.

TIMTOT is the maximum real time attained before the run is to stop; this stop must occur before damping is begun. It can be used to stop the program at a desired time in order to change the temperature distribution (see Subsection B.4).

Cards 6 through 11 describe the temperature distribution of the ring (see Subsection 2.2.2.1). If NTEMPS on Card 1 equals 1 (i.e., the ring has a uniform temperature distribution), then skip to Card 10; Cards 6 through 9 and 11 are to be left out.

CARD 6

	Card	Format
	LISTEM, IRAID, ICIRC	3I5

LISTEM can equal 1, 2, or 3 depending on the method used to describe the ring temperature distribution. The three methods corresponding to the value of LISTEM are as follows:

METHOD A, LISTEM = 1, the temperature corresponding to each flange in the ring will be read-in separately with input cards.

METHOD B, LISTEM = 2, the temperature of each flange will be calculated using functions chosen in Cards 8 or 9.

METHOD C, LISTEM = 3, the temperature of each flange is found by the program from a curve of temperature vs distance from the outside surface measured parallel to the z axis. The curve is approximated by coordinates given in Card(s) 11.

IRAID is used only if LISTEM = 2 (i.e., if Method B is used). If IRAID = 0, the temperature distribution through the thickness of the ring at $\theta = 0$ is read-in in Card 8. If IRAID = 1, the temperature distribution will be calculated using the following equation: (repeated from page 11).

$$T(K) = \frac{T_o}{H^2}\left(\zeta(K) - \frac{H}{2}\right)^2 - \frac{T_1}{H}\left(\zeta(K) - \frac{H}{2}\right) + T_2 \qquad \text{(repeated)}$$

where To, T1, and T2 are read-in on Card 9, H is the thickness of the ring, and $\zeta(K)$ is the distance to the K^{th} flange from the centroidal axis.

ICIRC is used only if LISTEM = 2.

If ICIRC = 1, the temperature distribution through the thickness, described previously using the value of IRAID, is constant around the circumference of the ring.

If ICIRC = 2, the above temperature distribution through the thickness varies as a function of $\sin\theta$ around the circumference of the ring as follows:

$$T(\theta,K)=(T(0,K)-TCOOL)\sin\theta+TCOOL$$

where $T(0,K)$ is the temperature of the K^{th} flange at $\theta = 0$

TCOOL is the ambient temperature of the ring before it was heated.

If ICIRC = 3, the temperature distribution through the thickness varies as a function of $\cos \theta/2$ around the circumference of the ring as follows:

$$T(\theta,K)=(T(0,K)-TCOOL)\cos\theta/2+TCOOL$$

Cards 7a,b... are used only if LISTEM on Card 6 equals 1.

Skip Card 7 if LISTEM does not equal 1.

<u>CARDS 7a, 7b</u>, ...

Card	Format
T(1,1), T(1,2), ..., T(I,K),..., T(N,NFL)	5E15.6

T(1,1) is the temperature of the first flange at the first link. The first "flange" is on the inner face of the ring (see Fig. 2a).

T(1,2) is the temperature of the second flange at the first mass point.

T(I,K) succeeding values of temperature are read, using as many data cards as are required, with five temperatures on a card (except possibly the last card) until all temperatures for NFL flanges at N links are read.

T(N,NFL)

If Cards 7 are used, skip to Card 12.

Cards 8a, b are used only if LISTEM = 2 and IRAID = 0 on Card 6. If these conditions are not met, skip Cards 8a and 8b.

CARDS 8a, 8b

Card	Format
T(1,1), T(1,2), ..., T(1,K), ..., T(1,NFL)	5E15.6

T(1,1) is the temperature of the first flange at $\theta = 0$. The first flange is on the inside of the ring.

T(1,2) is the temperature of the second flange at $\theta = 0$.

T(1,K) reading of succeeding values of T(1,K) continues until all temperatures for NFL flanges are read

T(1,NFL) at $\theta = 0$.

Card 9 is used only if LISTEM = 2 and IRAID = 1 on Card 6. If these conditions are not met, skip Card 9.

CARD 9

	Card	Format
	TZER, TONE, TTWO	3E15.6

TZER, TZONE, TTWO — are constant coefficients to be used in Eq. 1 on page 11. These are used to describe the temperature distribution through the ring thickness at $\theta = 0$. If Card 9 is used, skip to Card 12.

Card 10 is used only if the temperature of the ring is uniform (i.e., if NTEMPS = 1).

CARD 10

	Card	Format
	TCONST	E15.6

TCONST is the temperature of the uniformly heated ring in degrees. If a ring with no temperature effects assumed is being analyzed, set TCONST equal to TCOOL in Card 5. If Card 10 is used, skip to Card 12.

Cards 11 are used only if LISTEM = 3 (Method C) on Card 6. If LISTEM does not equal 3, skip these cards.

CARDS 11a, b, c, d, and e

	Card	Format
	TPOINT(1), DPOINT(1), TPOINT(2), DPOINT(2)	4E15.6

TPOINT(1), DPOINT(1) — are the coordinates of the first point (where the temperature at the outside surface of the ring (DPOINT(1) = 0) is given) on the temperature-versus-material depth curve as shown in Fig. 2C. TPOINT(1) and DPOINT(1) are in degrees and inches, respectively.

TPOINT(2) } are the coordinates of the second point on the temper-
DPOINT(2) } ature versus material depth curve.

Additional cards are punched until the required TEN coordinates approximating the curve are given. If a temperature is required for a depth greater than DPOINT(10), the program sets the value of temperature at that position equal to TCOOL.

This completes the description of the temperature distribution of the ring. Cards 12 through 16, which follow, give the information needed to calculate the temperature-dependent material properties of the ring. As outlined in Subsection 2.2.2.2, each flange is assigned values for material properties by the program based on a linear interpolation of curves of material "constant" versus temperature read on input cards.

CARD 12

Card	Format
TEA(1), TEA(2), ..., TEA(NTEMPS)	

TEA(1) is the lowest temperature level at which material properties will be given. Ordinarily, TEA(1) will be "room temperature" and will equal TCOOL given on Card 5, but this is not required, and TEA(1) can be any value as long as it does exceed the lowest temperature encountered on the ring; otherwise an error message will result and the program will stop.

TEA(2) is the next to lowest temperature level at which material properties are given.

TEA(NTEMPS) is the highest value of temperature at which material properties are given, where NTEMPS is given on Card 1 and is the total number of temperature levels given. NTEMPS cannot be less than 1 and not more than 5. TEA(NTEMPS) must be equal to or greater than the highest temperature encountered on the ring; otherwise, an error message will result and the program will stop. If the temperature of the ring is constant, and NTEMPS on Card 1 equals 1, set TEA(1) equal to TCONST on Card 10.

Card 13

Card	Format
ALPH(1), ALPH(2), ..., ALPH(NTEMPS)	5E15.6

ALPH(1) is the coefficient of thermal expansion for the first temperature level given, TEA(1), on Card 12 (inches/inch/degree)

ALPH(2) is the value given for the second temperature level given (TEA(2)).

ALPH(NTEMPS) is the value given for the highest value of temperature given (TEA(NTEMPS)). If ALPH is assumed to be independent of temperature, make all values required equal to the constant value since a value for each temperature level must be read by the computer.

Cards 14 and 15 should be included only if NORATE given in Card 1 equals 1. If NORATE equals zero, skip to Card 16.

CARD 14

Card	Format
DEA(1), DEA(2), ..., DEA(NTEMPS)	5E15.6

DEA(1) is the value of the constant D used in the strain-rate formula

$$\sigma_{y_\ell} = \sigma_{o_\ell} \left(1+\left|\frac{\dot{\varepsilon}}{D}\right|^{1/P} \right) \tag{B3}$$

for the first temperature level, where (D) = (1/sec), σ_{y_ℓ} is the rate dependent yield stress of subflange ℓ, and σ_{o_ℓ} is the static yield stress of subflange ℓ, where $\sigma_{o_\ell} = E_{1_\ell} \; \varepsilon_{o_\ell}$ (see Ref. 7)

DEA(2) is the value of the constant D for the second temperature level.

DEA(NTEMPS) is the value of the constant D for the highest temperature level. As for ALPH(NT), list NTEMPS values of DEA(NT) even though they may be all the same.

CARD 15

Card	Format
PEA(1), PEA(2), ..., PEA(NTEMPS)	5E15.6

PEA(1) is the value of the constant p used in Eq. B3 above for the first temperature level, where p is nondimensional.

PEA(2) is the value of p for the second temperature level

PEA(NTEMPS) is the value of the constant p for the highest temperature level. A value of PEA(NT) must be given for all temperature levels, even though they may all be the same.

The following card(s) must be included. They describe the material stress-strain curve for each temperature level.

CARD 16aa

Card	Format
EPS(1,1), SIG(1,1), EPS(2,1), SIG(2,1)	4E15.6

EPS(1,1) } make up the first coordinate pair of strain and stress
SIG(1,1) } in the first temperature level, which is used to define the polygonal approximation of the first temperature level's stress-strain diagram (see Fig. A.4a). The stress-strain diagram which these values, and those following, approximate, must be upwardly convex with nonnegative slopes. (ε (ℓ,NT) = in/in. and σ (ℓ,NT) = lb/in^2)

EPS(2,1) } make up the second pair in the first temperature level.
SIG(2,1) }

Additional cards 16 ab and 16 ac are punched in exactly the same manner as Card 16 aa until the number of coordinate pairs equals NSFL punched on Card 1. The total number of coordinate pairs must not exceed 5 for any temperature level. Do not include any unneeded (blank) cards.

Card(s) 16 is (are) repeated (16 ba, 16 bb...etc.) for each temperature level until the number of sets of cards equals NTEMPS (given in Card 1). The total number of sets of cards must not exceed 5.

This ends the description of the ring and its temperature distribution, the remaining cards complete the description of the external forcing functions.

CARD 17

Card	Format
IOTA, NV	2I5

IOTA can equal 0, 1, or 2, depending upon the distribution of the initial impulse on the ring's circumference (see Fig. 3).
If IOTA = 0 no impulse is to be introduced

If IOTA = 1 an impulse will be defined at pertinent mass stations by defining the appropriate radial and tangential components of the initial velocities of each mass point in Data Cards 18 (a, b, ---).

If IOTA = 2 a sine shaped initial velocity field, distributed over a specified number of mass points and oriented at a specified angle, tilt or β (see Fig. 3b), to the ring tangent is to be defined in Data Card 19.

NV

If IOTA = 1 NV is the total number of masses for which the velocity components are to be specified.

If IOTA = 2 NV is not used and can be set = 0,

If there is to be no impulse in the run, set IOTA = 0 and NV = 0 and skip to Card 20.

Card(s) 18 is (are) included <u>only</u> if IOTA = 1 in Card 17.

<u>CARD 18a</u>

	Card	Format
	$\boxed{\text{MASSNO, VRAD, VTAN}}$	(I5,2E15.6)

MASSNO is the station (mass point) number at which the velocity components VRAD and VTAN are to be applied.

VRAD,VTAN are the radial velocity and the tangential velocity, respectively, applied to MASSNO (inches/sec). VRAD is positive directed out, VTAN is positive directed counterclockwise. (see Fig. 3a)

Additional cards (18b, 18c ...) are punched in exactly the same manner until the total number of cards specifying the initial velocity equals NV given in Card 17. It is not necessary to list those mass points which have zero initial velocity.

Card 19 is included only if IOTA = 2 in Card 17.

CARD 19

Card	Format
MASSES, MSTART, VEEZ, TILT	(2I5,2E15.6)

MASSES is the number of masses over which the sine shaped impulse is to be distributed. This number must be odd.

MSTART is the number of the first mass in the group over which the sine shaped impulse is distributed. i.e., the impulse is applied to mass points (MSTART), to (MSTART + MASSES - 1).

VEEZ is the peak value of the sine-shaped impulse, in inches per second.

TILT is the angle at which the impulse is applied to the ring referenced to the counter clockwise directed tangent. (See Fig. 3), in degrees.

If there is to be no time dependent forcing function during the run, these cards will be the last required in the input deck.

The last card specifies the sine-shaped time varying force applied to the ring, if one is present (see Fig. 4). In all cases, the time history of the total force applied is a triangular shaped pulse, with the value of the force being zero at TBEGIN and TFINAL specified on Card 4, and the maximum peak value and the time at which it occurs is also specified on Card 4. The force is distributed over a specified number of masses in the shape of a half-sine wave, and there is a provision for specifying the velocity at which the pressure pulse travels along the ring circumference if desired. The direction of the force relative to the local tangent is also specified. The data required to specify the loading is described below.

CARD 20

Card	Format
NSTAT, MASSN, RPM, ANGL	(2I5,2E15.6)

NSTAT is the first mass point at the beginning of the forcing function (see Fig. 4).

MASSN is the number of masses over which the forcing function is distributed. This must be odd.

RPM is the revolutions per minute, positive in the counter-clockwise direction, at which the forcing function is traveling. If the forcing function distribution is stationary with time on the ring, set RPM = 0.0.

ANGL is the angle between the force vector and the clockwise directed tangent vector (see Fig. 4), in degrees.

B.2.2 Input for Special Cases of the General Stress-Strain Relations

In the following, which in each case must apply to the ring as a whole, the specific input data for three special cases of the general elastic, strain-hardening constitutive relation handled by the computer program are given. Only the relevant data are noted:

(1) Purely Elastic Case

Set NFL = 2, NSFL = 1 on Card 1 and make EPS(1,NT) and SIG(1,NT) on Card(s) 16 sufficiently high so that no plastic deformation occurs; for example, EPS(1,NT) = 1.0, SIG(1,NT) = E(NT) where NT is the particular temperature level being described.

(2) Elastic, Perfectly-Plastic Case

Set NSFL = 1 on Card 1 and make EPS(1,NT) = SIG(1,NT)/E(NT) on Card(s) 16.

(3) Elastic, Linear Strain-Hardening Case

Set NSFL = 2 on Card 1 and set EPS(1,NT) = SIG(1,NT)/E_1(NT) also EPS(2,NT), and SIG(2,NT) on Cards 16 are taken sufficiently high in order to avoid plastic deformation in the second subflange (see the description of the strain-hardening model in Ref. 3); for example, EPS(2,NT) = 1.0 and SIG(2,NT) = 1 - EPS (2,NT)/E_p(NT) + SIG(1,NT), where E_p(NT) are the slopes of the segments of the stress-strain curves at different temperatures in the plastic range.

B.3 Output

The printed output begins with a partial reiteration of the program input which identifies the problem solved. The information presented varies with the type of problem analyzed. An example output is presented at the end of this Appendix in Subsection B.7.

After the initial printout has been completed, the following information is printed out (this is done before the first cycle (J = 0); after cycle JPRINT has been completed; and at every JCYCLE cycles thereafter, for both artificial, JSTART = 0, and real, JSTART = 1, time regimes):

J = [J] TIME = [TIME] SEPARATION (IN.) = [SEP]
TOTAL ENERGY INPUT INTO RING = [TOTWRK] (IN-LB)

```
   INITIAL ELASTIC ENERGY    = [ELAMAX] (IN-LB)
   IMPULSIVE ENERGY INPUT    = [WORKIM] (IN-LB)
   EXTERNAL FORCE INPUT      = [TPWORK] (IN-LB)
TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS:
   KINETIC ENERGY OF RING    = [RINGKE] (IN-LB)
   ELASTIC ENERGY            = [ELASTW] (IN-LB)
   DAMPING ENERGY            = [TDWORK] (IN-LB)
   PLASTIC WORK              = [PLASTW] (IN-LB)
THE FORCE RESULTANT ACTING ON THE RING DURING THIS CYCLE IS [AMP]

I     V     W     N     M     EPSI     EPSE     YIELD
1    ...   ...   ...   ...   .....    .....    ......
2    ...   ...   ...   ...   .....    .....    ......


N    ...   ...   ...   ...   .....    .....    ......
```

where

J = computation time cycle number

TIME = Elapsed time corresponding to the end of cycle J (sec)

SEP = the distance from the front of the ring to the back as approximated by the difference in W between mass points 1 and N/2 (inches)

TOTWRK = Total work done by the initial impulsive and the forcing function added to the initial elastic energy present in the entire ring due to the imposed thermal stresses (in-lb). TOTWRK includes both the internal energy of the ring, and the energy used to accelerate the "rigid body" mass of the ring in the inertial coordinate system.

ELAMAX = The elastic strain energy stored in the entire ring at TIME = 0

WORKIM = Total work done by the initial impulsive loading on the entire ring in the inertial axis system

TPWORK = Total internal work done by the external forcing function on the entire ring

RINGKE = Kinetic energy of the entire ring in the inertial axis system

ELASTW = Current elastic strain energy stored in the entire ring

TDWORK = Internal energy removed from the ring by artificial damping

PLASTW = Plastic work done on the entire ring (in-lb)

AMP = Amplitude of force resultant acting on ring during current cycle

I = Mass point station number

V = The y-location v_i, of the ith mass point* (in)

N = Axial force N_i in the ith link (lb)

M = Bending moment M_i at the ith mass point station (in-lb)

EPSI = Strain on the inner surface of the ring at the ith mass point station

EPSE = Strain on the outer surface of the ring at the ith mass point station

Asterisks are printed below YIELD whenever plastic yielding occurs in any of the flanges at that station.

At the end of each run in which real time has been used, a statement FIRST YIELDING AT TIME = ... is printed out. This statement gives the time of the first plastic deformation ever to occur during the response. At that time, a printout of the above-illustrated kind is made (independent of the values of JPRINT and JCYCLE). If the response is purely elastic, no such statement or printout is made.

---

*The coordinates V and W of the mass points are measured from the original, time = zero, center of mass position of the ring.

B.4 Continuation Runs and Method to be Used for Varying Ring Temperature Distribution with Time

Included in the output of each completed run is a set of continuation cards which contains all of the information that is necessary to continue the same run, if desired, to obtain further time-history information with or without a different temperature distribution. Each completed continuation run also produces a continuation deck, so the process may be continued indefinitely as long as desired.

In general, there are three ways in which a JET 1 run can be completed. The first is to let the ring's dynamic motion be damped out in real time and the program will terminate itself when the ring is fully damped. The second is to specify JSTART = 0 for artificial time and make TIMTOT = 0.0. The motion of the ring due to the imposed thermal stresses will be damped out and because TIMTOT = 0, the run will terminate at real time equal zero. The third way is accomplished by specifying TIMTOT and HDAMP, where HDAMP is some time greater than TIMTOT (say 1.0 sec) and TIMTOT is the real time when the program should stop.

The third way of completing a run is the most useful if one desires to change temperature each time using the continuation run feature, since the stopping time is specified. However, all three methods yield a continuation deck and any of these can be continued if desired.

It should be noted that all continuation runs are made using real time (JSTART is set equal to 1 in the program for a continuation run) since no damping should be allowed in the middle of a run.

To continue a run, the input data should be submitted as follows:

Card Contents

1 N, NFL, NSFL, JPRINT, JCYCLE, MORE, JSTART, JFDAMP, NTEMPS, NORATE

same

same

determined by user

same

same (set = to 1 in program)

Nonzero positive integer (e.g., original run number)

same

New first print cycle

2 Same

3 DELTAT, HALT1, HALT2, TIMP

same

same

May have to be changed

If continuation run includes a new temperature distribution, then DELTAT may have to be changed; if DELTAT is set equal to zero, program will calculate an acceptable value.

4 Same as before, (time history of the applied forces occurring before, during or after start of continuation run is inconsequential).

5 HDAMP, FDAMP, TCOOL, TIMTOT

May have to be changed

same

May have to be changed if temperature changes.
Program will calculate correct value if set equal to 0.

Same (not used)

6 Are used to describe the temperature distribution on the ring,
7 and can be altered as desired to describe the new temperature
8 if desired. If temperature does not vary, leave those cards
9 used unchanged.
10
11
12 These cards describe the material properties of the ring, and
13 these should be left unaltered. Care must be taken, however,
14 to assure that no new ring temperatures are out of the bounds
15 given for the material properties.
16

← Put continuation cards here

17
18
19 Same as before
20

B.5 Partial List of Variable Names Used in the Program

SYMBOL	DESCRIPTION
ADDIT	Used in KOOLIT to find average value of SEP over 100 program cycles
ADELT1	Equals 360/N
ADELT2	Equals 180/N
AFL	Area of each flange in the ring
ALPH(NT)	Input quantities of thermal expansion coefficient vs temperature
ALPHA(I,K)	Thermal expansion coefficient of the material in the Kth flange at the Ith mass station

AMP	Value of the resultant total force acting on the ring at a particular time, pounds
AMPER	Equals DAMPER/DELTAT
ASFL(L,K,I)	Area of the Lth subflange in the Kth flange at the Ith mass station
ASTER	Equals an asterisk when printed in "A" format
AVE	Average value of SEP over 100 time cycles in KOOLIT
B	Width of ring
BIGKE1 BIGKE2	Values of ring kinetic energy at two consecutive peaks
BIGM(I)	Bending moment at the Ith mass station
BIGN(I)	Axial force at the Ith mass station
BLANK	Equals a blank space when printed in "A" format
BUGGER	Equals $(\text{DELTAT})^2/\text{PTMASS}$
C6	Equals 1.0/[D(I,K)*DELTAT*E(1,K,I)]
CHNGM	Change in momentum of ring caused by the external applied forces during the current run
CHNGMZ	Total lateral change in momentum of ring caused by the external applied forces during last (continued) run
COST(I)	Cosine of the angle the Ith link makes with the y-axis
D(I,K)	Constant used in the strain-rate formula for the Kth flange at the Ith mass station

DAMPER	Value of damping coefficient used to damp out elastic motion of the ring
DDS(I)	Circumferential change in length of the Ith link during the Jth cycle
DDTH(I)	Incremental change of the angle between the Ith and the (I+1)th link during the Jth cycle, plus if ring bends to increase ring curvature
DDV DDW	Elongation of the Ith link in the horizontal (y) and vertical (z) direction, respectively, during the Jth cycle
DEA(NT)	Input quantities of constant used in strain-rate formula vs temperature
DELLON DELLAT	Calculated values of DELTAT based on wave equation and lateral bending equation, respectively
DELTA	Interim value of depth of Kth flange from the outer surface of the ring measured parallel to the z-axis
DELTAT	Time interval per program cycle
DELR	Interim value of change in distance each mass point moves during first cycle after impulse
DELV DELW	Interim value of change in V(I) and W(I) due to impulsive loading during first cycle after impulse
DFY(I) DFZ(I)	Damping forces acting on Ith mass in horizontal and vertical directions, respectively
DHALF	Distance between flanges in the ring divided by two

DIAM	Calculated value of ring diameter
DPOINT(J)	Input value of depth on curve of temperature vs depth for Method C
DS(I)	Current length of Ith link
DSN	Total stress on the Kth flange at the Ith mass due to both axial and bending strain
DSZ	Initial link length
DTH(I)	Total link bending angle (curvature) summed from time = 0 between the Ith and the (I+1)th links
DTX(I)	Change in angle the Ith link makes with the horizontal from one time cycle to the next. Positive if link rotates counter-clockwise.
DV(I) DW(I)	Incremental change in position of the Ith mass point in the horizontal (y) and vertical (z) direction, respectively, during the Jth cycle.
DWCG	Shift in position of CG of the ring in the vertical direction due to the initial impulse
DWORK	Work done by damping forces during the Jth cycle
E(L,K,I)	Young's modulus of the Lth subflange, in the Kth flange, at the Ith mass station
EAVEB EAVET	Test values of effective cross sectional Young's modulus for bending and tension, respectively
ELAMAX	Initial elastic energy stored in ring due to initial temperature distribution

ELASTW	Total elastic energy present in the ring during the Jth cycle
EMAXB EMAXT	Maximum values of effective Young's modulus for cross-sectional bending and tension, respectively
EMINB	Minimum values of effective Young's modulus for cross-sectional bending and tension, respectively
EPS(L,NT)	Input quantities of absissa of stress-strain curves for the Lth subflange varying with temperature
EPSI(I) EPSE(I)	Strains on the inner and outer surfaces of the ring, respectively, at the Ith mass station
EPSIL(L,K,I)	Calculated value of absissa of the stress-strain curve for the Lth subflange in the Kth flange at the Ith mass station
ERTIA	Used in TEMPUS to calculate the maximum and minimum value of effective cross-sectional Young's modulus for bending
ES ET	Current values of strain in the outer fiber due to elongation and bending, respectively
FACTOR	Dummy variable used to interpolate temperature dependent material constants
FDAMP	Value used for damping real time elastic motion
FN	Axial force acting on the Kth flange
H	Thickness of the ring
HALT	Calculated value of ring's first elastic mode period

HALT1 HALT2	Input values of ring's first elastic mode period used for artificial and real time portions of the run, respectively
HDAMP	Value used for damping artificial time elastic motion
HHALF	Half the thickness of the ring
HSQU	Thickness of the ring squared
I	Mass subscript
I1, I2	The mass station numbers through which a given value of impulse-induced velocity acts
ICIRC	An input quantity which specifies what the circumferential distribution of the temperature is to be
IMP	A variable used to limit the calling of IMPULS
IOTA	An input quantity used to specify the type of initial impulse
IRAID	An input quantity used in specifying radial distribution of ring temperatures
J	Current cycle number
JBEGIN	Cycle number during which the triangular forcing function begins to act
JCYCLE	Printout will occur every JCYCLE cycles
JFDAMP	Used to limit running time in the artificial time portion of the run when desired
JIMP	Used in STOP to limit initialization
JMIN	Cycle number at which minimum separation occurs

JPRINT	Denotes cycle at which first printout should start
JSTART	Input value which tells program whether ring motion due to initial thermal stresses will be damped out before run is to begin
JUMP	Indicator which tells when ring reaches first peak separation in KOOLIT
JUSTPR	Used to call PRINT after RECORD is called
JZ	Final program cycle number for last (continued) run
K	Subscript referring to flange number. First flange forms inside of ring
KOOL	Used in KOOLIT to limit initialization
L	Used as a subscript for the subflanges
LIMIT	Dummy variable used in IDENT to printout existing temperatures
LINK	Takes on values of 1 through 5 to denote which stage program has completed for printout purposes
LISTEM	An input quantity which specifies which method will be used to specify ring temperatures
LOAD	Equal 1 means forcing function is acting Equal -1 means forcing function is not acting
MAB	Indicator, tells when ring separation changes direction of travel in KOOLIT
MAX1 MAX2	Used to identify first and second kinetic energy peak in STOP, respectively

MDET MP	Both quantities are used to round-off calculated value of DELTAT
MORE	An input quantity used to signal a continuation run
MPUNCH	The output tape unit for punching output quantities; this must be assigned a number (in MAIN) according to the user's computing facility
MREAD	The input tape unit name; this must be assigned a number (in MAIN) according to the user's computing facility
MWRITE	The printed output tape unit name; this must be assigned a number (in MAIN) according to the user's computing facility
MYIELD	Cycle during which the first yielding occurred
N	Total number of mass points in the semiring
N1	Equals N
NFL	Number of flanges in ring
NFL2	Equals NFL/2
NHALF	Equals N/2
NHALF1	Equals NHALF+1
NHIT	The last mass station acted upon by the initial impulse
NORATE	Input quantity indicating whether strain-rate effects are to be included or not
NSFL	Number of subflanges in each flange

NTEMPS	An input quantity which specifies the number of material property groups to be read in for interpolation in HEAT
NULLIT	Used in MAIN as an indicator when ring has been completely damped.
NV	Number of ranges of velocity used to express the initial impulse distribution when IOTA = 1
NYIELD	A dummy variable which calls PRINT when yielding first occurs
OLDT(I,K)	Temperature of the Kth flange at the Ith mass station during the last (continued) run
P(I,K)	Constant used in the strain-rate formula for the Kth flange at the Ith mass station
PASTKE	Ring kinetic energy from previous cycle
PEA(NT)	Input quantities of constant used in the strain-rate formula vs temperature
PFY(I) PFZ(I)	External forces acting on Ith mass segment in the horizontal and vertical directions, respectively
PIE	Equals 3.14159265
PLASTW	Total plastic work done up to the Jth cycle
PLEN	Duration of the forcing function
PTMASS	Mass of each mass point
PWORK	Work done by the external forces during the Jth cycle
Q(I)	Shear force acting at the Ith mass station

R	Distance from the center of the ring to its undeformed centroidal axis
RADIAN	Equals 57.2957795
RFLANJ(K)	Radius from the ring center to the Kth flange
RHO	Density of ring material
RIN	Inner radius of ring
RINGKE	Current value of the kinetic energy in the ring
RVEL	Used to calculate impulsively imparted radial velocity of the mass
SEP	Approximate separation distance between the front and back of the ring after the Jth cycle
SEPLAS	Previous cycle value of SEP
SEPMIN	Minimum and maximum values of SEP, respectively, for 100 cycle intervals
SIG(L,NT)	Input quantities of ordinate of stress-strain curves for the Lth subflange varying with temperature
SIGMA(L,K,I)	Calculated value of ordinate of stress-strain curve for the Lth subflange in the Kth flange at the Ith mass station
SINT(I)	Sine of the angle the Ith link makes with the Y-axis
SINTI	Interim value of SINT(I)
SMIN	Minimum separation between the front and the back of the ring

SMIN	Minimum separation between the front and the back of the ring
SN(L,K,I)	Stress on the Lth subflange in the Kth flange at the Ith mass station
SNY	Yield stress taking strain-rate effects into account
SNZ(L,K,I)	Yield stress of the Lth subflange in the Kth flange at the Ith mass station
T(I,K)	Temperature of the Kth flange at the Ith mass station
T1	Times at which the forcing function reaches its peak value
TBEGIN TFINAL	Times when the forcing function starts and stops acting, respectively
TCONST	An input quantity read in TEMPS when NTEMPS = 1. Equal to constant value of ring temperature
TCOOL	Ambient temperature of total ring before heating (undeformed state)
TDWORK	Current total energy removed from ring by artificial damping
TEA(NT)	Input quantities of temperature for each NTth level
THETA	Angle the Ith link makes with the y-axis (see Fig. 1)
TIME	Current time
TIMEZ	Final time at end of last (continued) run

TIMP	Time of occurrence of impulse loading for real time only (JSTART = 1)
TIMTOT	Real time at which run is to stop
TMIN	Time at which minimum separation occurs
TESTKE	Maximum kinetic energy that ring can possess before damping multiplyed by .001
TOTWRK	Total energy input to ring
TPOINT(J)	Input value of temperature on curve of temperature vs depth for Method C
TPWORK	Current total work done by external forces on the ring
TZER, TONE, TTWO	Input quantities used to define radial distribution of temperature
TZFORS	Sum of all the forces on the ring up to the present time
V(I), W(I)	Horizontal and vertical distances from the relative axis center to the Ith mass point
WORKIM	Energy contributed to the ring by impulse
YIELD(I)	Controls whether a blank or an asterisk is printed, according to an elastic or a plastically-strained flange condition, respectively
ZETA(K)	Distance from the Kth flange to the ring's cross-section center of gravity

B.6 FORTRAN IV Program Listing for JET 1

The following program and subroutines are listed in this subsection in the following order:

1 JET 1 Main Program
2 INPUT
3 INIT
4 TEMPS
5 HEAT
6 TEMPUS
7 IDENT
8 IMPULS
9 PREZZ
10 CYCLE
11 STRAIN
12 STRESS
13 EQUIL
14 KOOLIT
15 STOP
16 RECORD
17 PRINT
18 FINAL

```
C      JET 1 MAIN PROGRAM
       COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
      1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
      2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
      3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
      4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
      5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
      6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
      7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
      8CHNGMZ,CHNGM,TIMEZ,TIMYLD
       COMMON ALPH,AMP1,AMP2,       B,       CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
      1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
      2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C      INTEGER COMMON
       COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
      1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
      2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
      3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
      4JUSTPR,JZ
       DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
      1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
      2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
      3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
      4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
      5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
      60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
      7TA(10)
       MREAD=5
       MWRITE=6
       MPUNCH=7
       CALL INPUT
       NPRINT =JPRINT
       KOOL=0
       NYIELD=0
       CALL TEMPS
       CALL HEAT
       CALL TEMPUS
       DO 1 I=1,N
       DFY(I)=0.0
       PFY(I)=0.0
       DFZ(I)=0.0
       PFZ(I)=0.0
       SMASH(I)=0.0
     1 CONTINUE
       TZFORS=0.0
       BUGGER=DELTAT**2/PTMASS
C      CONTINUATION BRANCH
       IF(MORE) 9,9,8
     8 CALL FINAL
       GO TO 10
C      INITIALIZATION SECTION
     9 CALL INIT
    10 ELAST=0.0
       DO 13 I=1,N1
       DO 12 K=1,NFL
       DO 11 L=1,NSFL
C      INITIALIZE THERMAL STRESSES
       SN(L,K,I)=SN(L,K,I) -E(1,K,I)*ALPHA(I,K)*(T(I,K)-OLDT(I,K))
       IF(MORE.GT.0.0) ELAST=ELAST+SN(L,K,I)**2*ASFL(L,K,I)/E(1,K,I)
    11 CONTINUE
```

```
   12 CONTINUE
   13 CONTINUE
      IF(MORE.GT.0.0) ELAMAX=ELAMAX+ELAST*DSZ-ELASTW
      IMP=0
      CALL IMPULS
      CALL IDENT
      IF(JSTART) 14,14,29
C
C     ARTIFICIAL TIME FOR DAMPING RING MOTION DUE TO INITIAL THERMAL STRESSE
C
   14 IF(HALT1) 16,15,16
C     CALCULATE CONSERVATIVE ESTIMATE OF TIME NEEDED FOR PLASTICITY TO CEASE
   15 HALT=2.*PIE*R**2* SQRT(3.*RHO/EMINB)/H
      HALT1=HALT
   16 LINK=1
      CALL RECORD
      BUGGER=BUGGER/2.
      CALL CYCLE
      BUGGER=BUGGER*2.
   17 CALL CYCLE
      IF(HALT1) 18,18,19
C     TEST SEPARATION PEAKS FOR END OF PLASTICITY
   18 CALL KOOLIT
      HALT1=HALT
      IF(HALT1) 17,17,20
   19 IF(HALT1-TIME) 20,20,17
C     PLASTICITY IS CONSIDERED OVER
   20 LINK=2
      CALL RECORD
C     DAMPING OF ELASTIC MOTION STARTS HERE
      IF(HDAMP) 22,22,21
   21 DAMPER=HDAMP
      GO TO 23
C     CALCULATE DAMPING FACTOR
   22 DAMPER=PIE*H*B*0.80*SQRT(EMINT*RHO)/NHALF
   23 JIMP=0
      AMPER=DAMPER/DELTAT
   24 CALL CYCLE
      CALL STOP
      IF(JFDAMP.LT.J) GO TO 26
      IF(NULLIT.LE.0) GO TO 24
C     ELASTIC MOTION HAS CEASED
   25 LINK=3
      CALL RECORD
   26 J=-1
      JSTART=1
      TIME=0.0
      MYIELD=0
      DAMPER=0.0
      AMPER=0.0
      TDWORK=0.0
      PLASTW=0.0
      DO 27 I=1,N
      DFZ(I)=0.0
      DFY(I)=0.0
   27 CONTINUE
      IF(TIMTOT.LE.0.0) GO TO 28
      LINK=6
      CALL RECORD
      SMIN=DIAM
```

```
      TMIN=0.0
      JPRINT=NPRINT
      GO TO 29
   28 LINK=4
      CALL RECORD
      CALL FINAL
      CALL EXIT
C
C     REAL TIME STARTS HERE
C
   29 IF(HALT2) 31,30,31
C     CALCULATE CONSERVATIVE ESTIMATE OF TIME NEEDED FOR PLASTICITY TO CEASE
   30 HALT=2.*PIE*R**2* SQRT(3.*RHO/EMINB)/H
      HALT2=HALT
   31 IF(MORE.EQ.1) GO TO 32
      BUGGER=BUGGER/2.
      CALL CYCLE
      BUGGER=BUGGER*2.
   32 CALL CYCLE
      IF(TIME.GE.TIMTOT) GO TO 42
   33 IF((TIME.LT.TIMP).OR.(TIME.LT.TFINAL)) GO TO 32
C     ALL EXTERNAL FORCES HAVE CEASED
      IF(HALT2.GT.0.0) HALT2=HALT2+TIME
   34 CALL CYCLE
      IF(TIME.GE.TIMTOT) GO TO 42
      IF(HALT2) 35,35,36
   35 CALL KOOLIT
      HALT2=HALT
      IF(HALT2) 34,34,37
   36 IF(TIME.LE.HALT2) GO TO 34
C     PLASTICITY IS CONSIDERED OVER
   37 LINK=5
      CALL RECORD
C     DAMPING OF ELASTIC MOTION STARTS HERE
      IF(FDAMP) 39,39,38
   38 DAMPER=FDAMP
      GO TO 40
   39 DAMPER=PIE*H*B*0.80*SQRT(EMINT*RHO)/NHALF
   40 AMPER=DAMPER/DELTAT
      JIMP=0
   41 CALL CYCLE
      CALL STOP
      IF(NULLIT.LE.0) GO TO 41
C     ELASTIC MOTION HAS CEASED
      LINK=3
      CALL RECORD
   42 CALL FINAL
      CALL EXIT
```

```
      SUBROUTINE INPUT
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,      B,       CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      READ(MREAD,1) N,NFL,NSFL,JPRINT,JCYCLE,MORE,JSTART,JFDAMP,NTEMPS,N
     1ORATE
    1 FORMAT(10I5)
      READ(MREAD,2) R,B,H,RHO,DELTAT,HALT1,HALT2,TIMP,TBEGIN,TFINAL,AMP1
     1,T1,HDAMP,FDAMP,TCOOL,TIMTOT
    2 FORMAT(4E15.6)
      LOAD=-1
      DAMPER=0.0
      N1=N
      NHALF=N/2
      NHALF1=NHALF+1
      NFL2=NFL/2
      HHALF=H/2.
      HSQU=H**2
      DHALF=HHALF/NFL
      AFL=B*H/NFL
      RADIAN=57.2957795
      PIE=3.14159265
      DSZ=2.*R* SIN(PIE/N)
      ADELT1=360./N
      ADELT2=180./N
      DIAM=2.*R
      PTMASS=2.*RHO*B*H*PIE*R/N
      DO 3 K=1,NFL2
      L=NFL-K+1
      ZETA(K)=DHALF*(L-K)
      ZETA(L)=-ZETA(K)
    3 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE INIT
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGYZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,       B,        CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      DATA ASTER/'*'/,BLANK/' '/
      NYIELD=0
      MYIELD=0
      J=-1
      TIME=0.0
      TDWORK=0.0
      TPWORK=0.0
      JZ=0
      TOTWRK=0.0
      WORKIM=0.0
      ELAMAX=0.0
      TOTKE=0.0
      PLASTW=0.0
      ELASTW=0.0
      TIMEZ=0.0
      DO 6 I=1,N1
      RVELZ(I)=0.0
      DV(I)=0.0
      DW(I)=0.0
      DS(I)=DSZ
      DTH(I)=0.0
      EPSI(I)=0.0
      EPSE(I)=0.0
      YIELD(I)=BLANK
      BIGN(I)=0.0
      BIGM(I)=0.0
      DO 5 K=1,NFL
      DO 4 L=1,NSFL
      SN(L,K,I)=0.0
    4 CONTINUE
    5 CONTINUE
    6 CONTINUE
      N4=N/4
```

```
      BIT=ADELT1/RADIAN
      THETA=-ADELT2/RADIAN
      THETA2=-BIT
      DO 7 I=1,N4
      THETA=THETA+BIT
      NIT2=NHALF1-I
      NIT3=NHALF+I
      NIT4=N-I+1
      V(I)=R* SIN(THETA)
      W(I)=-R* COS(THETA)
      V(NIT2)=V(I)
      W(NIT2)=-W(I)
      V(NIT3)=-V(I)
      W(NIT3)=W(NIT2)
      V(NIT4)=V(NIT3)
      W(NIT4)=W(I)
    7 CONTINUE
      N34=3*N4
      DO 71 I=1,N4
      THETA2=THETA2+BIT
      COST(I)=COS(THETA2)
      SINT(I)=SIN(THETA2)
      COST(I+N4)=-SINT(I)
      SINT(I+N4)=COST(I)
      COST(I+NHALF)=-COST(I)
      SINT(I+NHALF)=-SINT(I)
      COST(I+N34)=SINT(I)
      SINT(I+N34)=-COST(I)
   71 CONTINUE
      SEP=DIAM
      SMIN=DIAM
      TIMYLD=0.0
      TMIN=0.0
      JMIN=0
      DO 8 I=1,N1
      DO 8 K=1,NFL
      OLDT(I,K)=TCOOL
    8 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TEMPS
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EV
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,        B,        CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      DIMENSION RELANJ(10),TPOINT(10),DPOINT(10)
      IF(NTEMPS-1)1,21,1
    1 READ(MREAD,2)LISTEM,IRAID,ICIRC
    2 FORMAT(3I5)
      GO TO (3,5),LISTEM
    3 READ(MREAD,4) ((T(I,K),K=1,NFL),I=1,N1)
    4 FORMAT(5E15.6)
      RETURN
    5 IF(IRAID) 9,6,9
    6 READ(MREAD,7) (T(1,K),K=1,NFL)
    7 FORMAT(5E15.6)
      GO TO 12
    9 READ(MREAD,10) TZER,TONE,TTWO
   10 FORMAT(3E15.6)
      DO 11 K=1,NFL
      T(1,K)=TZER*(ZETA(K)-HHALF)**2/HSQU-TONE*(ZETA(K)-HHALF)/H+TTWO
   11 CONTINUE
   12 GO TO(13,15,18),ICIRC
C     CONSTANT AROUND CIRCUMFERENCE
   13 DO 14 I=2,N1
      DO 14 K=1,NFL
      T(I,K)=T(1,K)
   14 CONTINUE
      RETURN
C     SIN THETA VARIATION AROUND CIRCUMFERENCE
   15 DO 17 I=1,NHALF1
      TIK= SIN(ADELT1*(I-1)/RADIAN)
      DO 16 K=1,NFL
      T(I,K)=TCOOL+(T(1,K)-TCOOL)*TIK
      IF(I.GT.1) T(N-I+2,K)=T(I,K)
   16 CONTINUE
   17 CONTINUE
      RETURN
```

```
C        COS HALF THETA VARIATION AROUND CIRCUMFERENCE
   18 DO 20 I=1,NHALF1
      TIK= COS(ADELT2*(I-1)/RADIAN)
      DO 19 K=1,NFL
      T(I,K)=TCOOL+(T(1,K)-TCOOL)*TIK
      IF(I.GT.1) T(N-I+2,K)=T(I,K)
   19 CONTINUE
   20 CONTINUE
      RETURN
   21 READ(MREAD,22) TCONST
   22 FORMAT(E15.6)
      DO 24 I=1,N1
      DO 23 K=1,NFL
      T(I,K)=TCONST
   23 CONTINUE
   24 CONTINUE
      RETURN
   25 READ(MREAD,26) (TPOINT(NT),DPOINT(NT),NT=1,10)
   26 FORMAT(4E15.6)
      RIN=R-HHALF
      ROUT=R+HHALF
      DO 27 K=1,NFL
      RFLANJ(K)=RIN+(2*K-1)*DHALF
   27 CONTINUE
      DO 33 I=1,NHALF
      THETA=ADELT2*(2*I-1)/RADIAN
      DO 33 K=1,NFL
      IF(THETA-1.5707964) 29,29,28
   28 IF(RFLANJ(K)*SIN(THETA)-RIN) 31,29,29
   29 DELTA=SQRT(ROUT**2-RFLANJ(K)**2*SIN(THETA)**2)-RFLANJ(K)*COS(THETA
     1)
      IF.DELTA.LT.DPOINT(1)) GO TO 34
      DO 30 IP=2,10
      IF(DELTA-DPOINT(IP)) 32,32,30
   30 CONTINUE
   31 T(I,K)=TCOOL
      GO TO 33
   32 T(I,K)=TPOINT(IP)+(TPOINT(IP-1)-TPOINT(IP))*(DPOINT(IP)-DELTA)/(DP
     1OINT(IP)-DPOINT(IP-1))
   33 CONTINUE
      DO 330 I=1,NHALF
      DO 330 K=1,NFL
      NOPP=N-I+1
  330 T(NOPP,K)=T(I,K)
      RETURN
   34 WRITE(MWRITE,35)
   35 FORMAT(' WHEN CALCULATING TEMPERATURE USING METHOD C, THE TEMPERAT
     1URE AT THE OUTSIDE SURFACE MUST BE GIVEN IN DATA INPUT')
      CALL EXIT
      END
```

```
      SUBROUTINE HEAT
C     THIS SUBROUTINE DEFINES THE TEMPERATURE DEPENDENT MATERIAL CONSTANTS
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,        B,        CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      READ(MREAD,1)(TEA(NT),NT=1,NTEMPS)
      READ(MREAD,1)(ALPH(NT),NT=1,NTEMPS)
      IF(NORATE.EQ.0)GO TO 23
      READ(MREAD,1)(DEA(NT),NT=1,NTEMPS)
      READ(MREAD,1)(PEA(NT),NT=1,NTEMPS)
    1 FORMAT(5E15.6)
   23 DO 3 NT=1,NTEMPS
      READ(MREAD,2)(EPS(L,NT),SIG(L,NT),L=1,NSFL)
    2 FORMAT(4E15.6)
    3 CONTINUE
      DO 22 I=1,N1
      DO 21 K=1,NFL
      IF(NTEMPS-1) 4,4,6
C     NO TEMPERATURE VARIATION
    4 ALPHA(I,K)=ALPH(1)
      IF(NORATE.EQ.0)GO TO 24
      D(I,K)=DEA(1)
      P(I,K)=PEA(1)
      GO TO 25
   24 D(I,K)=0.0
   25 DO 5 L=1,NSFL
      EPSIL(L,K,I)=EPS(L,1)
      SIGMA(L,K,I)=SIG(L,1)
    5 CONTINUE
      GO TO 16
C     CALCULATION OF TEMPERATURE DEPENDENT MATERIAL CONSTANTS
    6 NT=1
    7 NT=NT+1
   29 IF(T(I,K)-TEA(NT-1))9,13,8
    8 IF(NT-NTEMPS)11,11,28
    9 IF(TEA(NT-1).EQ.0.0) GO TO 28
      ERROR= ABS(T(I,K)/TEA(NT-1))
```

```
      IF(ABS(ERROR-1.).GT..001) GO TO 28
      T(I,K)=TEA(NT-1)
      GO TO 13
   28 WRITE(MWRITE,10) I,K,T(I,K)
   10 FORMAT('      TEMPERATURE OF RING IS OUTSIDE RANGE OF INPUT VALUES
     1OF CONSTANTS, AT I=',I3,',K=',I3/'      TEMPERATURE IN QUESTION IS'
     2E15.6)
      CALL EXIT
   11 IF(T(I,K)-TEA(NT))12,13,7
   12 FACTOR=(T(I,K)-TEA(NT-1))/(TEA(NT)-TEA(NT-1))
      GO TO 14
   13 FACTOR=0.0
   14 ALPHA(I,K)=ALPH(NT-1)+FACTOR*(ALPH(NT)-ALPH(NT-1))
      IF(NORATE.EQ.0) GO TO 26
      D(I,K)=DEA(NT-1)+FACTOR*(DEA(NT)-DEA(NT-1))
      P(I,K)=PEA(NT-1)+FACTOR*(PEA(NT)-PEA(NT-1))
      GO TO 27
   26 D(I,K)=0.0
   27 DO 15 L=1,NSFL
      EPSIL(L,K,I)=EPS(L,NT-1)+FACTOR*(EPS(L,NT)-EPS(L,NT-1))
      SIGMA(L,K,I)=SIG(L,NT-1)+FACTOR*(SIG(L,NT)-SIG(L,NT-1))
   15 CONTINUE
   16 E(1,K,I)=SIGMA(1,K,I)/EPSIL(1,K,I)
      IF(NSFL-1)19,19,17
   17 DO 18 L=2,NSFL
      E(L,K,I)=(SIGMA(L,K,I) -SIGMA(L-1,K,I))/(EPSIL(L,K,I)-EPSIL(L-1,K,
     1I))
   18 CONTINUE
   19 E(NSFL+1,K,I)=0.0
      DO 20 L=1,NSFL
      ASFL(L,K,I)=AFL*(E(L,K,I)-E(L+1,K,I))/E(1,K,I)
      SNZ(L,K,I)=E(1,K,I)*EPSIL(L,K,I)
   20 CONTINUE
   21 CONTINUE
   22 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TEMPUS
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,       B,       CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      ERTIA=0.0
      EMAXB=0.0
      EMAXT=0.0
      DO 1 K=1,NFL
      EMAXB=EMAXB+E(1,K,1)*ZETA(K)**2
      EMAXT=EMAXT+E(1,K,1)
      ERTIA=ERTIA+ZETA(K)**2
    1 CONTINUE
      TERTIA=H**2/12.
      EMINB=EMAXB
      EMINT=EMAXT
      IF(NTEMPS.EQ.1) GO TO 4
      DO 3 I=2,N1
      EAVEB=0.0
      EAVET=0.0
      DO 2 K=1,NFL
      EAVEB=EAVEB+E(1,K,I)*ZETA(K)**2
      EAVET=EAVET+E(1,K,I)
    2 CONTINUE
      IF(EAVEB.GT.EMAXB) EMAXB=EAVEB
      IF(EAVEB.LT.EMINB) EMINB=EAVEB
      IF(EAVET.GT.EMAXT) EMAXT=EAVET
      IF(EAVET.LT.EMINT) EMINT=EAVET
    3 CONTINUE
    4 EMAXT=EMAXT/NFL
      EMINT=EMINT/NFL
      EMAXB=EMAXB/ERTIA
      EMINB=EMINB/ERTIA
      IF(DELTAT.GT.0.0) GO TO 11
      DELLON=DSZ/ SQRT(EMAXT/RHO)
      DELLAT=DSZ**2/2./SQRT(EMAXB*TERTIA/RHO)
      IF(DELLON-DELLAT) 6,5,5
    5 DELTAT=DELLAT
```

```
      GO TO 7
    6 DELTAT=DELLON
    7 DO 8 MP=1,15
      DELTAT=DELTAT*10.
      IF(DELTAT-10.0) 8,10,10
    8 CONTINUE
      WRITE(MWRITE,9)
    9 FORMAT('INCREASE LIMIT ON STATMENT 7, SUBRT TEMPUS FOR DELTAT DETE
     1RMINATION')
      CALL EXIT
   10 MDET=DELTAT*.45
      DELTAT=MDET*2
      MP=-MP
      DELTAT= DELTAT*10.0**MP
      RETURN
   11 DELLAT=0.0
      RETURN
      END
```

```
      SUBROUTINE IDENT
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,        B,        CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      WRITE(MWRITE,1)
    1 FORMAT('1')
      IF(MORE.GT.0) WRITE(MWRITE,2) MORE
    2 FORMAT('     THIS RUN IS A CONTINUATION OF RUN',I3,' OF'//)
      WRITE(MWRITE,3) R,B,H,N,NFL,NSFL,NTEMPS
    3 FORMAT('     JET 1.......A PROGRAM USED TO CALCULATE THE RESPONSE OF
     1 A FREE'/'     CIRCULAR HEATED RING WITH THE FOLLOWING PARAMETERS..
     2..'//'     RADIUS OF RING TO CENTROID (IN.)',20X,'='F10.6/
     3'     WIDTH OF RING (IN.)',33X,'='F10.6/
     4'     THICKNESS OF RING (IN.)',29X,'='F10.6//
     5'     NUMBER OF MASS POINTS USED IN WHOLE RING',12X,'='I5/
     6'     NUMBER OF FLANGES USED IN RING CROSS SECTION',8X,'='I5/
     7'     NUMBER OF SUBFLANGES USED IN STRAIN HARDENING MODEL ='I5/
     8'     NUMBER OF TEMPERATURE LEVELS USED TO DESCRIBE'/
     9'      TEMPERATURE DEPENDENT MATERIAL PROPERTIES',10X,'='I5)
      IF(NTEMPS-1) 5,4,5
    4 WRITE(MWRITE,34) TCONST
   34 FORMAT('0    THE TEMPERATURE OF THE RING IS A CONSTANT AND IS EQUAL
     1 TO',F8.2,' DEGREES')
      GO TO 14
    5 LIMIT=N1/4+1
      NEXT(1)=-3
      WRITE(MWRITE,6)
    6 FORMAT('0    PRESENT RING TEMPERATURES, T(I,K), ARE AS FOLLOWS...')
      DO 13 I=1,LIMIT
      NEXT(1)=NEXT(1)+4
      DO 7 NEX=2,4
      NEXT(NEX)=NEXT(NEX-1)+1
      MEX=NEX
      IF(NEXT(NEX).EQ.N1) GO TO 8
    7 CONTINUE
    8 WRITE(MWRITE,9) (NEXT(NE),NE=1,MEX)
    9 FORMAT(//14X,2HI=,4(I3,15X))
```

```
      WRITE(MWRITE,10)
   10 FORMAT(1H0)
      NEX1=NEXT(1)
      NEXMEX=NEXT(MEX)
      DO 12 K=1,NEL
      WRITE(MWRITE,11) K,(T(II,K),II=NEX1,NEXMEX)
   11 FORMAT(3H K=,I3,2X,4(2X,E14.8,2X))
   12 CONTINUE
   13 CONTINUE
   14 IF(DELLAT) 17,17,15
   15 WRITE(MWRITE,16) DELLAT,DELLON
   16 FORMAT('0    TIME INTERVAL BASED ON LATERAL VIBRATION EQUATION ='E1
     15.8/,'     TIME INTERVAL BASED ON LONGITUDINAL VIBRATION EQUATION =
     2'E15.8)
   17 WRITE(MWRITE,18) DELTAT
   18 FORMAT(//'      TIME INTERVAL PER CYCLE USED IN PROGRAM (SEC) ='E15.
     18/)
      IF(IOTA) 21,19,21
   19 WRITE(MWRITE,20)
   20 FORMAT('0    THERE IS NO IMPULSIVE LOADING')
      GO TO 30
   21 GO TO (24,26),IOTA
   24 WRITE(MWRITE,25)
   25 FORMAT('0     AN ARBITRARY IMPULSE LOADING HAS BEEN SPECIFIED AS DE
     1SCRIBED BY INPUT CARDS')
      GO TO 30
   26 WRITE(MWRITE,27)
   27 FORMAT('0     A LOCALIZED SINE SHAPED IMPULSE LOADING HAS BEEN SPEC
     1IFIED')
   30 IF(TFINAL.EQ.0.0) GO TO 32
      PLEN=TFINAL-TBEGIN
      WRITE(MWRITE,31) TBEGIN,TFINAL,PLEN
   31 FORMAT ('0    STARTING TIME OF FORCING FUNCTION (SEC.)   ='F10.7/,
     1'     STOPPING TIME (SEC.)   ='F10.7/,'     DURATION   (SEC.)   ='F10.7
     2)
      RETURN
   32 WRITE(MWRITE,33)
   33 FORMAT('0     THERE IS NO TIME VARYING FORCING FUNCTION DURING THIS
     1 RUN')
      RETURN
      END
```

```
      SUBROUTINE IMPULS
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,      B,      CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      DIMENSION VDEL(101),WDEL(101)
      IF(IMP.EQ.1) GO TO 11
      READ(MREAD,1) IOTA,NV
    1 FORMAT(2I5,5X,E15.6)
      IF(IOTA.EQ.0)  GO TO 15
      GO TO (90,94),IOTA
   90 DO 91 I=1,N
      VDEL(I)=0.0
   91 WDEL(I)=0.0
   92 FORMAT(I5,2E15.6)
      DO 93 IMAZ=1,NV
      READ(MREAD,92) MASSNO,VRAD,VTAN
      IF(MASSNO.GT.N) GO TO 101
      THETA=ADELT2*(2*MASSNO-1)/RADIAN
      VDEL(MASSNO)=(VRAD*SIN(THETA)+VTAN*COS(THETA))*DELTAT
   93 WDEL(MASSNO)=(-VRAD*COS(THETA)+VTAN*SIN(THETA))*DELTAT
      NHIT=MASSNO
      GO TO 10
C     ASSUME SINE DISTRIBUTION, NOTE..., NO. OF MASSES MUST BE ODD
   94 READ(MREAD,95) MASSES,MSTART, VEEZ,TILT
   95 FORMAT(2I5,2E15.6)
      DO 941 I=1,N
      VDEL(I)=0.0
  941 WDEL(I)=0.0
      TILT=TILT*PIE/180.
      DTETA=PIE/((MASSES-1)*2)
      WIDTH=PIE/(MASSES-1)
      EXTRA(2)=VEEZ
      ALESS=0
      MASS2=1+MASSES/2
      DO 97 KAREA=1,MASS2
      MAZZ=MSTART-1+KAREA
      MAZZA=MSTART+MASSES-KAREA
```

```
      THETA=ADELT2*(2*MAZZ-1)/RADIAN
      TATA=((KAREA-1)*2+1)*DTETA
      VCITY=VEEZ*(1-COS(TATA))/WIDTH-ALESS
      ALESS=ALESS+VCITY
      VRAD=VCITY*SIN(TILT)
      VTAN=VCITY*COS(TILT)
      VDEL(MAZZ)=(VRAD*SIN(THETA)+VTAN*COS(THETA))
      WDEL(MAZZ)=(-VRAD*COS(THETA)+VTAN*SIN(THETA))
      THETA=ADELT2*(2*MAZZA-1)/RADIAN
      VDEL(MAZZA)=(VRAD*SIN(THETA)+VTAN*COS(THETA))
   97 WDEL(MAZZA)=(-VRAD*COS(THETA)+VTAN*SIN(THETA))
      WRITE(MWRITE,98)
   98 FORMAT('0INITIAL VELOCITY INPUT IS AS FOLLOWS...'/)
      DO 100 KAREA=1,MASSES
      MAZZ=MSTART-1+KAREA
      WRITE(MWRITE,99)MAZZ,VDEL(MAZZ),WDEL(MAZZ)
   99 FORMAT(' MASS POINT',I3,' VDEL =',F10.2,' WDEL =',F10.2)
      VDEL(MAZZ)=VDEL(MAZZ)*DELTAT
      WDEL(MAZZ)=WDEL(MAZZ)*DELTAT
  100 CONTINUE
      NHIT=MSTART+MASSES-1
   10 IMP=1
      RETURN
  101 WRITE(MWRITE,102)
  102 FORMAT('1THERE IS AT LEAST ONE MASS NUMBER GIVEN FOR IMPULSE INITI
     1AL VELOCITY WHICH IS GREATER THAN THE STATED NUMBER OF MASSES,'/,
     2'PLEASE CHECK YOUR DATA...')
      CALL EXIT
   11 WORKIM=0.0
  121 DO 122 I=1,NHIT
      WORKIM=WORKIM+VDEL(I)**2+WDEL(I)**2
      DV(I)=DV(I)+VDEL(I)
      DW(I)=DW(I)+WDEL(I)
  122 CONTINUE
C      IMPULSE KINETIC ENERGY
  123 WORKIM=WORKIM*PTMASS/DELTAT**2/2.
   15 IMP=-1
      RETURN
      END
```

```
      SUBROUTINE PREZZ
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,F,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,        B,        CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      DIMENSION FS(100),EFIND(100)
      IF(LOAD.EQ.1) GO TO 10
      READ(MREAD,6) NSTAT,MASSN,RPM,ANGL
    6 FORMAT(2I5,2E15.6)
      FTOTZ=AMP1
      T2=TFINAL
      CIRC=2.*PIE*R
      CIRCR=CIRC*RPM/60.
      DSZH=DSZ/2.
      FTOT1=FTOTZ/(T1-TBEGIN)
      FTOT2=FTOTZ/(T2-T1)
      TILT=ANGL*PIE/180.
      STILT=SIN(TILT)
      CTILT=COS(TILT)
      PIEP=PIE/DSZ/(MASSN-1)
   10 ARCL=CIRCR*(TIME-TBEGIN)
      NMASS=(ARCL+DSZH)/DSZ
      KSTAT=NSTAT+NMASS
      BIT=ARCL-NMASS*DSZ+DSZ/2.
      DO 20 I=1,N
      PFY(I)=0.0
   20 PFZ(I)=0.0
      TOTAL=0.0
      IF(TIME-T1) 30,30,40
   30 FTOT=FTOT1*TIME
      GO TO 50
   40 FTOT=FTOT2*(T2-TIME)
   50 FATOR=FTOT/2.
      DO 80 I=1,MASSN
      MAZ=KSTAT-1+I
      MINOS=I-1
      ANGLE=PIEP*(BIT+DSZ*MINOS)
      IF(ANGLE-PIE) 70,70,60
```

```
60 ANGLE=PIE
70 FS(MAZ)=1.-COS(ANGLE)-TOTAL
   TOTAL=TOTAL+FS(MAZ)
   FS(MAZ)=FS(MAZ)*FATOR
   PFY(MAZ)=-FS(MAZ)*CTILT
80 PFZ(MAZ)=FS(MAZ)*STILT
   AMP=0.0
   NSTOP=KSTAT+MASSN-1
   DO 90 MASS=KSTAT,NSTOP
   EFIND(MASS)=SQRT(PFY(MASS)**2+PFZ(MASS)**2)
90 AMP=AMP+EFIND(MASS)
   RETURN
   END
```

```
      SUBROUTINE CYCLE
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,F,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,      B,      CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      J=J+1
      JUSTPR=0
      CALL STRAIN
      CALL STRESS
      TIME=(J-JZ)*DELTAT+TIMEZ
      IF(JSTART.LT.1) GO TO 3
      IF((TIME.GE.TFINAL).OR.(TIME.LT.TBEGIN)) GO TO 1
      CALL PREZZ
      LOAD=1
      GO TO 2
    1 LOAD=-1
    2 IF((IMP.LT.1).OR.(TIME.LT.TIMP))GO TO 4
      CALL IMPULS
      IMP=-1
      GO TO 4
    3 LOAD=-1
    4 CALL EQUIL
      SEPLAS=SEP
      SEP=W(NHALF)-W(1)
      IF(SEP-SMIN)5,6,6
    5 SMIN=SEP
      TMIN=TIME
      JMIN=J
    6 IF(J-JPRINT)7,9,12
    7 IF(J) 8,10,8
    8 IF(NYIELD) 13,13,10
    9 JPRINT=JPRINT+JCYCLE
   10 CALL PRINT
      NYIELD=0
   11 GO TO 14
   12 JPRINT=J+JCYCLE
   13 IF(MORE.EQ.1) CALL PRINT
   14 RETURN
      END
```

```
      SUBROUTINE STRAIN
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,        B,       CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATF,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      DO 1 I=2,N
      DDV=DV(I)-DV(I-1)
      DDW=DW(I)-DW(I-1)
      DDS(I)=DDV*COST(I)+DDW*SINT(I)
      DTX(I)=(DDW*COST(I)-DDV*SINT(I))/DS(I)
      SINTI=SINT(I)
      SINT(I)=SINT(I)+COST(I)*DTX(I)
      COST(I)=COST(I)-SINTI*DTX(I)
    1 CONTINUE
      DDV=DV(1)-DV(N)
      DDW=DW(1)-DW(N)
      DDS(1)=DDV*COST(1)+DDW*SINT(1)
      DTX(1)=(DDW*COST(1)-DDV*SINT(1))/DS(1)
      SINTI=SINT(1)
      SINT(1)=SINT(1)+COST(1)*DTX(1)
      COST(1)=COST(1)-SINTI*DTX(1)
      IF(SINT(1).LT..1E-08) SINT(1)=0.0
      NM1=N-1
      DO 2 I=1,NM1
      DDTH(I)=DTX(I+1)-DTX(I)
      DTH(I)=DTH(I)+DDTH(I)
    2 CONTINUE
      DDTH(N)=DTX(1)-DTX(N)
      DTH(N)=DTH(N)+DDTH(N)
      DO 3 I=1,N
      V(I)=V(I)+DV(I)
      W(I)=W(I)+DW(I)
      DS(I)=DS(I)+DDS(I)
    3 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STRESS
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,      B,      CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      DATA ASTER/'*'/,BLANK/' '/
      DO 16 I=1,N1
      YIELD(I)=BLANK
      BIGN(I)=0.0
      BIGM(I)=0.0
      DO 15 K=1,NFL
      DSN=E(1,K,I)*(DDS(I)-DDTH(I)*ZETA(K))/DSZ
      FN=0.0
      IF(D(I,K).LE.0.0) GO TO 1
      PIK=1.0/P(I,K)
      C6=1.0/D(I,K)/DELTAT/E(1,K,I)
    1 DO 14 L=1,NSFL
      SN(L,K,I)=SN(L,K,I)+DSN
      IF(DAMPER.GT.0.0) GO TO 13
      IF(D(I,K).LE.0.0) GO TO 7
      IF(SN(L,K,I)-SNZ(L,K,I))2,13,5
    2 IF(SN(L,K,I)+SNZ(L,K,I))3,13,13
    3 SNY=SNZ(L,K,I)*(1.0+(C6* ABS(DSN))**PIK)
      IF(SN(L,K,I)+SNY)4,13,13
    4 SN(L,K,I)=-SNY
      GO TO 11
    5 SNY=SNZ(L,K,I)*(1.0+(C6* ABS(DSN))**PIK)
      IF(SN(L,K,I)-SNY)13,13,6
    6 SN(L,K,I)=SNY
      GO TO 11
    7 IF(SN(L,K,I)-SNZ(L,K,I))9,13,8
    8 SN(L,K,I)=SNZ(L,K,I)
      GO TO 11
    9 IF(SN(L,K,I)+SNZ(L,K,I))10,13,13
   10 SN(L,K,I)=-SNZ(L,K,I)
   11 YIELD(I)=ASTER
      IF(MYIELD)13,12,13
   12 MYIELD=J
```

```
      TIMYLD=TIME
      NYIELD=1
   13 FN=FN+SN(L,K,I)*ASFL(L,K,I)
   14 CONTINUE
      BIGN(I)=BIGN(I)+FN
      BIGM(I)=BIGM(I)+FN*ZETA(K)
   15 CONTINUE
   16 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE EQUIL
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,       B,       CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      DWORK=0.0
      PWORK=0.0
      ZFORS=0.0
    5 DO 6 I=2,N
      Q(I)=(BIGM(I)-BIGM(I-1))/DS(I)
    6 CONTINUE
      Q(1)=(BIGM(1)-BIGM(N))/DS(1)
      IF(DAMPER)9,9,7
    7 DO 8 I=1,N
      DFY(I)=-DV(I)*AMPER
      DFZ(I)=-DW(I)*AMPER
    8 CONTINUE
    9 DO 10 I=1,N
      K=I+1
      IF(I.EQ.N) K=1
      DV(I)=DV(I)+BUGGER*(BIGN(K)*COST(K)-BIGN(I)*COST(I)-Q(K)*SINT(K)+Q
     1(I)*SINT(I)+PFY(I)+DFY(I))
      DW(I)=DW(I)+BUGGER*(BIGN(K)*SINT(K)-BIGN(I)*SINT(I)+Q(K)*COST(K)-Q
     1(I)*COST(I)+PFZ(I)+DFZ(I))
      PWORK=PWORK+PFY(I)*DV(I)+PFZ(I)*DW(I)
      DWORK=DWORK-DFY(I)*DV(I)-DFZ(I)*DW(I)
   10 CONTINUE
      TPWORK=TPWORK+PWORK
      TDWORK=TDWORK+DWORK
      IF(LOAD.LT.0) GO TO 12
      DO 11 I=1,N
      PFY(I)=0.0
      PFZ(I)=0.0
   11 CONTINUE
   12 RETURN
      END
```

```
      SUBROUTINE KOOLIT
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,      B,      CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      HALT=-1
      IF(KOOL.GT.0)GO TO 2
      KOOL=1
      MIB=0
      MAB=0
      SEPMAX=0.0
      SEPMIN=PIE*R
      JUMP=0
      AVE=0.0
      ADDIT=0.0
    2 MIB = MIB+1
      ADDIT = ADDIT+SEP
      IF(MIB.LT.100) RETURN
    3 AVE=ADDIT/100.
      ADDIT=0.0
      MIB=0
    8 IF(JUMP) 10,10,9
    9 MAB=-1*MAB
      JUMP=-1
   10 IF(MAB) 19,11,14
C     FIRST TIME THROUGH
   11 IF(AVE-DIAM) 12,24,13
C     SEP DECREASING
   12 MAB=-1
      GO TO 24
C     SEP INCREASING
   13 MAB=1
      GO TO 24
C     SEP INCREASED LAST TIME
   14 IF(AVE-SEPMAX) 16,15,15
C     NEW MAXIMUM SEP
   15 SEPMAX=AVE
      GO TO 24
```

```
C       SEP AT A PEAK
   16 IF(JUMP) 17,18,18
C       SECOND PEAK
   17 HALT=1
      RETURN
C       FIRST PEAK
   18 JUMP=1
      GO TO 24
C       SEP DECREASED LAST TIME
   19 IF(AVE-SEPMIN) 20,20,21
C       NEW MINIMUM SEP
   20 SEPMIN=AVE
      GO TO 24
C       SEP AT A MINIMUM
   21 IF(JUMP) 22,23,23
C       SECOND MINIMUM
   22 HALT=1
      RETURN
C       FIRST MINIMUM
   23 JUMP=1
   24 RETURN
      END
```

```
      SUBROUTINE STOP
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,        B,       CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      IF(JIMP)1,1,3
    1 BIGKE1=0.0
    2 BIGKE2=0.0
      NULLIT=0
      TOTKE=ELAMAX+TPWORK+WORKIM-PLASTW
      TESTKE=TOTKE*.001
    3 JIMP=JIMP+1
C     CALCULATE RING KINETIC ENERGY
      RINGKE=0.0
      DO 4 I=1,N
      RINGKE=RINGKE+DV(I)**2+DW(I)**2
    4 CONTINUE
      RINGKE=RINGKE/BUGGER
      IF(BIGKE1.LT.RINGKE) BIGKE1=RINGKE
      IF(JIMP.LT.100) RETURN
      JIMP=1
      IF(BIGKE1.LT.TESTKE) NULLIT=1
      BIGKE1=0.0
      RETURN
      END
```

```
      SUBROUTINE RECORD
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,      B,      CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      DIMENSION STREZ(10)
      GO TO (1,3,5,13,15,17),LINK
    1 WRITE(MWRITE,2)
    2 FORMAT('1JSTART=0 HAS BEEN SPECIFIED'/,' THEREFORE, RESPONSE OF RI
     1NG TO INITIAL STRESSES DUE TO IMPOSED TEMPERATURE DISTRIBUTION FOL
     2LOWS USING ARTIFICIAL TIME...'/,' NO EXTERNAL FORCES WILL BE INCLU
     3DED UNTIL EITHER PLASTICITY IS CONSIDERED FINISHED AND RING MOTION
     4 IS DAMPED OUT OR UNTIL SPECIFIED.' )
      RETURN
    3 WRITE(MWRITE,4) J,TIME,SEP
    4 FORMAT('1PLASTICITY IS CONSIDERED FINISHED AT CYCLE NO.'I5,', THE
     1ARTIFICIAL TIME IS'F12.9/' THE PRESENT RING SEPARATION IS'F12.9/'.
     2..DAMPING OF THE ELASTIC MOTION STARTS IMMEDIATELY.')
      IF(JUSTPR.EQ.0) CALL PRINT
      RETURN
    5 WRITE(MWRITE,6) TIME,DAMPER
    6 FORMAT('1RING ELASTIC REPONSE WAS ARTIFICIALLY DAMPED AT' F10.6,
     1' SEC'/,' USING A DAMPING VALUE OF'F7.3,' LB-SEC/IN.'/,' MOTION IS
     2 CONSIDERED COMPLETELY DAMPED.'//)
      WRITE(MWRITE,7) (K,K=1,NFL)
    7 FORMAT(' THE FINAL EQUILIBRIUM STRESS DISTRIBUTION IS AS FOLLOWS..
     1.'//,'   I      K =',10(I3,9X))
      WRITE(MWRITE,8)
    8 FORMAT('0')
      DO 12 I=1,N1
      DO 10 K=1,NFL
      FN=0.0
      DO 9 L=1,NSFL
      FN=FN+SN(L,K,I)*ASFL(L,K,I)
    9 CONTINUE
      STREZ(K)=FN/AFL
   10 CONTINUE
      WRITE(MWRITE,11) I,(STREZ(K),K=1,NFL)
```

```
11 FORMAT(I5,1X,10E12.4)
12 CONTINUE
   IF(JUSTPR.EQ.0) CALL PRINT
   RETURN
13 WRITE(MWRITE,14)
14 FORMAT(//' NO EXTERNAL FORCES HAVE BEEN SPECIFIED...'///)
   RETURN
15 WRITE(MWRITE,16) J,TIME,SEP
16 FORMAT('1PLASTICITY IS CONSIDERED FINISHED AT CYCLE NO.'I5,/,' THE
  1 REAL TIME IS'F12.9,' THE PRESENT RING SEPARATION IS'F12.9/,'...DA
  2MPING OF THE ELASTIC MOTION STARTS IMMEDIATELY.')
   IF(JUSTPR.EQ.0) CALL PRINT
   RETURN
17 WRITE(MWRITE,18) SMIN,TMIN
18 FORMAT('1THE ARTIFICIAL TIME PHASE OF THE RUN HAS BEEN COMPLETED,'
  1/' THE REAL TIME PORTION STARTS IMMEDIATELY...'///
  2'  THE MINIMUM SEPARATION REACHED BY THE RING DURING THE ARTIFICIA
  3L TIME PORTION OF THE RUN ='F10.6/'  ARTIFICIAL TIME OF MINIMUM SE
  4PARATION ='F10.7)
   RETURN
   END
```

```
      SUBROUTINE PRINT
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,       B,       CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      JUSTPR=1
C
C     CALCULATION OF RING ENERGY DISTRIBUTION
C
      RINGKE=0.0
      DO 1 I=1,N
      RINGKE=RINGKE+DV(I)**2+DW(I)**2
    1 CONTINUE
C     KINETIC ENERGY OF TOTAL RING
      RINGKE=RINGKE/2./BUGGER
      IF(J.EQ.0.AND.MORE.EQ.0) RINGKE=RINGKE/2.
      ELASTW=0.0
      DO 4 L=1,NSFL
      DO 3 K=1,NFL
      DO 2 I=1,N
      ELASTW=ELASTW+SN(L,K,I)**2*ASFL(L,K,I)/E(1,K,I)
    2 CONTINUE
    3 CONTINUE
    4 CONTINUE
C     ELASTIC ENERGY OF TOTAL RING
      ELASTW=ELASTW*DSZ/2.
      MORE=0
      IF(J.EQ.0) ELAMAX=ELASTW
      TOTWRK=TPWORK+WORKIM+ELAMAX
      PLASTW=TOTWRK-ELASTW-TDWORK-RINGKE
C     DETERMINATION OF STRAINS AT INNER AND OUTER SURFACES
      DO 5 I=1,N
      ES=DS(I)-DSZ
      ET=HHALF*DTH(I)
      EPSI(I)=(ES-ET)/DSZ
      EPSE(I)=(ES+ET)/DSZ
    5 CONTINUE
C
```

```
C       PRINT-OUT RESULTS
C
        WRITE(MWRITE,6) J,TIME,SEP
      6 FORMAT('1     J='I5,'   TIME='F10.7,5X,'SEPARATION (IN.) ='F9.5)
        WRITE(MWRITE,8) TOTWRK,ELAMAX,WORKIM,TPWORK
      8 FORMAT(5X,'TOTAL ENERGY INPUT INTO RING ='F10.3, ' (IN-LB)'/7X,
       1'INITIAL ELASTIC ENERGY       ='F10.3,' (IN-LB)'/
       27X,'IMPULSIVE ENERGY INPUT       ='F10.3,' (IN-LB)'/
       37X,'EXTERNAL FORCE INPUT         ='F10.3,' (IN-LB)')
        WRITE(MWRITE,9) RINGKE,ELASTW,TDWORK,PLASTW
      9 FORMAT(//,5X,'TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS...'
       1/7X,'KINETIC ENERGY OF RING       ='F10.3,' (IN-LB)'/
       27X,'ELASTIC ENERGY',13X,'='F10.3,' (IN-LB)'/
       37X,'DAMPING ENERGY',13X,'='F10.3,' (IN-LB)'/
       47X,'PLASTIC WORK',15X,'='F10.3,' (IN-LB)')
        IF(LOAD) 10,12,12
     10 WRITE(MWRITE,11)
     11 FORMAT('0     NO FORCE ACTING DURING THIS CYCLE')
        GO TO 35
     12 WRITE(MWRITE,13) AMP
     13 FORMAT('0     THE FORCE RESULTANT ACTING ON THE RING DURING THIS CY
       1CLE IS',F12.4)
     35 WRITE(MWRITE,36)
     36 FORMAT(100H0      I           V             W              N
       1   M            EPSI          EPSE          YIELD)
        DO 38 I=1,N
        WRITE(MWRITE,37)I,V(I),W(I),BIGN(I),BIGM(I),EPSI(I),EPSE(I),YIELD(
       1I)
     37 FORMAT(I7,2F14.8,2F14.5,2F14.8,6X,A2)
     38 CONTINUE
        RETURN
        END
```

```
      SUBROUTINE FINAL
      COMMON ADELT1,ADELT2,AFL,ALPHA,AMP,AMPER,ASFL,BIGKE1,BIGKE2,
     1BIGM,BIGN,BUGGER,COST,DAMPED,DAMPER,DELLON,DELLAT,DELTAT,DD
     2S,DDTH,DFY,DFZ,DHALF,D,DS,DSZ,DTH,DTX,DV,DW,DWCG,DWORK,E,EM
     3AXB,EMAXT,EMINB,EMINT,EPSI,EPSE,ERTIA,EXTRA,EPSIL,FDAMP,G,H
     4ALT,HALT1,HALT2,HDAMP,HHALF,HSQU,OLDT,P,PASTKE,PFY,PFZ,PIE,
     5PTMASS,PWORK,Q,RADIAN,RINGKE,RVELZ,SEP,SEPLAS,SEPMIN,SEPMAX,SIGMA
     6,SINT,SMASH,SMIN,SN,SNZ,T,TDWORK,TIME,TPWORK,TYME,TZFORS,V,THETA,
     7W,ZETA,ZFORS,TMIN,AVE,TOTKE,PLASTW,ELAMAX,WORKIM,ELASTW,TOTWRK,
     8CHNGMZ,CHNGM,TIMEZ,TIMYLD
      COMMON ALPH,AMP1,AMP2,      B,      CONVRT,DEA,DIAM,EPS,H,PEA,PI,P
     1ISPR,PR,R,RHO,SIG,SLOPE,SWITCH,T1,T2,TBEGIN,TCONST,TCOOL,TE
     2A,TFINAL,TIMP,TRIMP,TZER,TONE,TTWO,TZ,YIELD,TIMTOT
C     INTEGER COMMON
      COMMON ICIRC,IMP,IOTA,IRAID,J,JCYCLE,JFDAMP,JIMP,JMIN,JOLT,I2,
     1JPRINT,JSTART,JTOTAL,KOOL,LINK,LISTEM,LOAD,MORE,MPUNCH,MREA
     2D,MWRITE,MYIELD,N,NFL,NFL2,NHALF,NHALF1,NLIM,NSFL,NTEMPS,NU
     3LLIT,NV,NYIELD,N1,NEXT,NORATE,NGIVEN,NREAD,LASTPR,JOLT2,JBEGIN,
     4JUSTPR,JZ
      DIMENSION ALPH(5),ALPHA(101,10),ASFL(5,10,101),BIGM(101),BIGN(
     1101),COST(101),D(101,10),DDS(101),DDTH(101),DEA(5),DFY(101)
     2,DFZ(101),DS(101),DTH(101),DTX(101),DV(101),DW(101),E(6,10,101),E
     3PS(5,5),EPSI(101),EPSE(101),EPSIL(5,10,101),EXTRA(100),G(101),N
     4EXT(15),OLDT(101,10),P(101,10),PEA(10),PFY(101),PFZ(101),Q(101),
     5RVELZ(101),SIG(5,5),SIGMA(5,10,101),SINT(101),SMASH(101),SN(5,1
     60,101),SNZ(5,10,101),T(101,10),TEA(5),V(101),W(101),YIELD(101),ZE
     7TA(10)
      IF(MORE) 1,1,9
    1 IF(JUSTPR.EQ.0) CALL PRINT
      IF(MYIELD) 4,4,2
    2 WRITE(MWRITE,3) TIMYLD
    3 FORMAT('0   FIRST YIELDING AT TIME ='F10.6)
    4 CONTINUE
      WRITE(MPUNCH,6) J,MYIELD,TIME,SMIN,TMIN,TIMYLD,TOTWRK,TPWORK,TDWOR
     1K,WORKIM,ELAMAX,ELASTW
      DO 8 I=1,N1
      WRITE(MPUNCH,7) V(I),DV(I),W(I),DW(I),DS(I),DTH(I),SINT(I),COST(I)
      WRITE(MPUNCH,7)(T(I,K),K=1,NFL)
      WRITE(MPUNCH,7)((SN(L,K,I),K=1,NFL),L=1,NSFL)
    8 CONTINUE
      CALL EXIT
    9 READ(MREAD,6) JZ,MYIELD,TIMEZ,SMIN,TMIN,TIMYLD,TOTWRK,TPWORK,TDWOR
     1K,WORKIM,ELAMAX,ELASTW
    6 FORMAT(2I5,4E15.8/(5E15.8))
      DO 10 I=1,N1
      READ(MREAD,7) V(I),DV(I),W(I),DW(I),DS(I),DTH(I),SINT(I),COST(I)
      READ(MREAD,7) (OLDT(I,K),K=1,NFL)
      READ(MREAD,7)((SN(L,K,I),K=1,NFL),L=1,NSFL)
    7 FORMAT(5E15.8)
   10 CONTINUE
      J=JZ
      JSTART=1
      RETURN
      END
```

B.7 Illustrative Example

The following example is presented to assist the user in checking the adaptation of JET 1 to his computer facility. The problem chosen is the one used to supply the position data for TEJ 1 mentioned in Subsection 3.4.1. In this example, a 7.3375 inch midsurface radius, 0.125 inch thick, 6061-T6 unheated aluminum ring, 1.0 inch long is acted upon by a triangularly shaped forcing function lasting .0004 sec. with a peak value of 10,000 pounds at $t = .0002$ sec. The total force is assumed to be distributed over a 25° segment of the ring with its amplitude defined by the shape of a half-sine wave over this sector.

The stress-strain curve for 6061-T6 aluminum can be approximated by the following stress-strain coordinates (σ,ε): (0 psi, 0 in/in); (42,500, .00425); 50,000, .030); and (65,000, .140). Strain rate effects are considered negligible, and the density is taken to be 0.25×10^{-3} lb.sec^2/in^4.

The number of mass points to be used to describe the complete ring is 72 and the ring's cross section will be represented by 4 flanges.

The critical time interval for this ring is obtained by using the smaller of the two critical times from Eqs. B1 and B2. These are calculated as follows:

$$\Delta T_{LONG} = \frac{\Delta S}{\sqrt{\frac{E}{\rho}}} = \frac{2\pi R}{N}\sqrt{\frac{\rho \varepsilon_1}{\sigma_1}} = .320 \times 10^{-5}$$

$$\Delta T_{LAT} = \frac{\frac{1}{2}(\Delta S)^2}{\sqrt{\frac{EI}{\rho H}}} = \frac{\sqrt{3}\,(\Delta S)^2}{H\sqrt{\frac{E}{\rho}}} = 2.96\ \Delta T_{LONG}$$

ΔT_{LONG} is the smaller of the two. A value less than this and convenient for plotting is desired, thus, $\Delta T = .25 \times 10^{-5}$ sec is chosen. Let the program compute 240 cycles (.000600 seconds); a print-out is desired at 40 cycles, and every 40 cycles thereafter.

B.7.1 Input Data

The values to be punched on the data cards are as follows:

Card 1 N = 72 FORMAT 10I5

NFL = 4

NSFL = 3

JPRINT = 40

JCYCLE = 40

MORE = 0 (this is not a continuation run)

JSTART = 1 (only real time will be used)

JFDAMP = 0

NTEMPS = 1

NORATE = 0 (no strain rate effects)

Card 2 R = .733750E+01 FORMAT 4E15.6

B = .100000E+01

H = .125000E+00

RHO = .250000E-03

Card 3 DELTAT = .250000E-05 FORMAT 4E15.6

HALT 1 = .000000E+00 (not used since JSTART = 1)

HALT 2 = .100000E+01 (the motion is not to be damped out)

TIMP = .000000E+00 (not used since there is no impulse)

Card 4	TBEGIN = .000000E+00 TFINAL = .400000E-03 AMP 1 = .100000E+05 T1 = .200000E-03		FORMAT 4E15.6
Card 5	HDAMP = .000000E+00 FDAMP = .000000E+00 TCOOL = .750000E+02 TIMTOT = .600000E-03	not used since JSTART = 1 not used	FORMAT 4E15.6
Cards 6-9	are not required since NTEMPS = 1		
Card 10	TCONST = .750000E+02		FORMAT E15.6
Card 11	is not required since NTEMPS = 1		
Card 12	TEA(1) = .750000E+02		FORMAT E15.6
Card 13	ALPH(1) = .123000E-04	(this could be anything since there is no temperature rise in the ring)	FORMAT E15.6
Cards 14 and 15	are not required since NORATE = 0		
Card 16a	EPS(1,1) = .425000E-02 SIG(1,1) = .425000E+05 EPS(2,1) = .300000E-01 SIG(2,1) = .50000E+05		FORMAT 4E15.6
Card 16b	EPS(3,1) = .140000E+00 SIG(3,1) = .650000E+05		FORMAT 2E15.6
Card 17	IOTA = 0 (no impulse is included) NV = 0 (not needed)		FORMAT 2I.5
Cards 18 and 19	SKIP since IOTA = 0		

Card 20 NSTAT = 35 (start of forcing function distribution) FORMAT 2I.5 2E15.6

MASSN = 5

RPM = .000000E+00 (the location at which the force is applied does not change)

ANGL = .210000E+02 (inclination angle)

The input data for this example problem should appear as follows for the 12 data cards actually used:

```
 72    4    3   40   40    0    1    0    1    0
+0.733750E+01  +0.100000E+01  +0.125000E+00  +0.250000E-03
+0.250000E-05  +0.000000E+00  +0.100000E+01  +0.000000E+00
+0.000000E+00  +0.400000E-03  +0.100000E+05  +0.200000E-03
+0.000000E+00  +0.000000E+00  +0.750000E+02  +0.600000E-03
+0.750000E+02
+0.750000E+02
+0.123000E-04
+0.425000E-02  +0.425000E+05  +0.300000E-01  +0.500000E+05
+0.140000E+00  +0.650000E+05
  0    0
 35    5  +0.000000E+00  +0.210000E+02
```

B.7.2 Results

The following is the sample output which should be obtained from JET 1 using the input data given on the preceding page. The first part of the output contains a partial reiteration of the program input. The remainder of the output gives the conditions of the ring at the following program cycle numbers, and corresponding "real" times: J = 0, TIME = 0.0 second; 38,0.000095 (corresponds to the time at which yielding first occurs); 40,0.000100; 80,0.000200; 120,000300; 160,0.000400; 200,0.000500; 240,0.000600.

```
JET 1......A PROGRAM USED TO CALCULATE THE RESPONSE OF A FREE
CIRCULAR HEATED RING WITH THE FOLLOWING PARAMETERS....

RADIUS OF RING TO CENTROID (IN.)                        =  7.337500
WIDTH OF RING (IN.)                                     =  1.000000
THICKNESS OF RING (IN.)                                 =  0.125000

NUMBER OF MASS POINTS USED IN WHOLE RING                =   72
NUMBER OF FLANGES USED IN RING CROSS SECTION            =    4
NUMBER OF SUBFLANGES USED IN STRAIN HARDENING MODEL =    3
NUMBER OF TEMPERATURE LEVELS USED TO DESCRIBE
 TEMPERATURE DEPENDENT MATERIAL PROPERTIES              =    1

THE TEMPERATURE OF THE RING IS A CONSTANT AND IS EQUAL TO    75.00 DEGREES


TIME INTERVAL PER CYCLE USED IN PROGRAM (SEC) = 0.24999999E-05


THERE IS NO IMPULSIVE LOADING

STARTING TIME OF FORCING FUNCTION (SEC.)  = 0.0
STOPPING TIME (SEC.)  = 0.0004000
DURATION  (SEC.)  = 0.0004000
```

J= 0 TIME= 0.0 SEPARATION (IN.) = 14.66103

TOTAL ENERGY INPUT INTO RING = 0.0 (IN-LB)
INITIAL ELASTIC ENERGY = 0.0 (IN-LB)
IMPULSIVE ENERGY INPUT = 0.0 (IN-LB)
EXTERNAL FORCE INPUT = 0.0 (IN-LB)

TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS...
KINETIC ENERGY OF RING = 0.0 (IN-LB)
ELASTIC ENERGY = 0.0 (IN-LB)
DAMPING ENERGY = 0.0 (IN-LB)
PLASTIC WORK = 0.0 (IN-LB)

THE FORCE RESULTANT ACTING ON THE RING DURING THIS CYCLE IS 0.0

I	V	W	N	M	EPSI	EPSE	YIELD
1	0.32005709	-7.33051586	0.0	0.0	0.0	0.0	
2	0.95773494	-7.27472687	0.0	0.0	0.0	0.0	
3	1.58812428	-7.16357231	0.0	0.0	0.0	0.0	
4	2.20642662	-6.99789810	0.0	0.0	0.0	0.0	
5	2.80793762	-6.77896595	0.0	0.0	0.0	0.0	
6	3.38807869	-6.50844193	0.0	0.0	0.0	0.0	
7	3.94243336	-6.18838501	0.0	0.0	0.0	0.0	
8	4.46678543	-5.82123089	0.0	0.0	0.0	0.0	
9	4.95714188	-5.40977383	0.0	0.0	0.0	0.0	
10	5.40977097	-4.95714378	0.0	0.0	0.0	0.0	
11	5.82122803	-4.46678734	0.0	0.0	0.0	0.0	
12	6.18838215	-3.94243717	0.0	0.0	0.0	0.0	
13	6.50843811	-3.38808537	0.0	0.0	0.0	0.0	
14	6.77896118	-2.80794907	0.0	0.0	0.0	0.0	
15	6.99789333	-2.20644188	0.0	0.0	0.0	0.0	
16	7.16356754	-1.58814240	0.0	0.0	0.0	0.0	
17	7.27472305	-0.95775682	0.0	0.0	0.0	0.0	
18	7.33051491	-0.32008237	0.0	0.0	0.0	0.0	
19	7.33051491	0.32008237	0.0	0.0	0.0	0.0	
20	7.27472305	0.95775682	0.0	0.0	0.0	0.0	
21	7.16356754	1.58814240	0.0	0.0	0.0	0.0	
22	6.99789333	2.20644188	0.0	0.0	0.0	0.0	
23	6.77896118	2.80794907	0.0	0.0	0.0	0.0	
24	6.50843811	3.38808537	0.0	0.0	0.0	0.0	
25	6.18838215	3.94243717	0.0	0.0	0.0	0.0	
26	5.82122803	4.46678734	0.0	0.0	0.0	0.0	
27	5.40977097	4.95714378	0.0	0.0	0.0	0.0	
28	4.95714188	5.40977383	0.0	0.0	0.0	0.0	
29	4.46678543	5.82123089	0.0	0.0	0.0	0.0	
30	3.94243336	6.18838501	0.0	0.0	0.0	0.0	
31	3.38807869	6.50844193	0.0	0.0	0.0	0.0	
32	2.80793762	6.77896595	0.0	0.0	0.0	0.0	
33	2.20642662	6.99789810	0.0	0.0	0.0	0.0	
34	1.58812428	7.16357231	0.0	0.0	0.0	0.0	
35	0.95773494	7.27472687	0.0	0.0	0.0	0.0	
36	0.32005709	7.33051586	0.0	0.0	0.0	0.0	
37	-0.32005709	7.33051586	0.0	0.0	0.0	0.0	
38	-0.95773494	7.27472687	0.0	0.0	0.0	0.0	
39	-1.58812428	7.16357231	0.0	0.0	0.0	0.0	
40	-2.20642662	6.99789810	0.0	0.0	0.0	0.0	
41	-2.80793762	6.77896595	0.0	0.0	0.0	0.0	
42	-3.38807869	6.50844193	0.0	0.0	0.0	0.0	
43	-3.94243336	6.18838501	0.0	0.0	0.0	0.0	
44	-4.46678543	5.82123089	0.0	0.0	0.0	0.0	
45	-4.95714188	5.40977383	0.0	0.0	0.0	0.0	
46	-5.40977097	4.95714378	0.0	0.0	0.0	0.0	
47	-5.82122803	4.46678734	0.0	0.0	0.0	0.0	
48	-6.18838215	3.94243717	0.0	0.0	0.0	0.0	
49	-6.50843811	3.38808537	0.0	0.0	0.0	0.0	
50	-6.77896118	2.80794907	0.0	0.0	0.0	0.0	
51	-6.99789333	2.20644188	0.0	0.0	0.0	0.0	
52	-7.16356754	1.58814240	0.0	0.0	0.0	0.0	
53	-7.27472305	0.95775682	0.0	0.0	0.0	0.0	
54	-7.33051491	0.32008237	0.0	0.0	0.0	0.0	
55	-7.33051491	-0.32008237	0.0	0.0	0.0	0.0	
56	-7.27472305	-0.95775682	0.0	0.0	0.0	0.0	
57	-7.16356754	-1.58814240	0.0	0.0	0.0	0.0	
58	-6.99789333	-2.20644188	0.0	0.0	0.0	0.0	
59	-6.77896118	-2.80794907	0.0	0.0	0.0	0.0	
60	-6.50843811	-3.38808537	0.0	0.0	0.0	0.0	
61	-6.18838215	-3.94243717	0.0	0.0	0.0	0.0	
62	-5.82122803	-4.46678734	0.0	0.0	0.0	0.0	
63	-5.40977097	-4.95714378	0.0	0.0	0.0	0.0	
64	-4.95714188	-5.40977383	0.0	0.0	0.0	0.0	
65	-4.46678543	-5.82123089	0.0	0.0	0.0	0.0	
66	-3.94243336	-6.18838501	0.0	0.0	0.0	0.0	
67	-3.38807869	-6.50844193	0.0	0.0	0.0	0.0	
68	-2.80793762	-6.77896595	0.0	0.0	0.0	0.0	
69	-2.20642662	-6.99789810	0.0	0.0	0.0	0.0	
70	-1.58812428	-7.16357231	0.0	0.0	0.0	0.0	
71	-0.95773494	-7.27472687	0.0	0.0	0.0	0.0	
72	-0.32005709	-7.33051586	0.0	0.0	0.0	0.0	

J= 38 TIME= 0.0000950 SEPARATION (IN.) = 14.68270

TOTAL ENERGY INPUT INTO RING = 120.293 (IN-LB)
INITIAL ELASTIC ENERGY = 0.0 (IN-LB)
IMPULSIVE ENERGY INPUT = 0.0 (IN-LB)
EXTERNAL FORCE INPUT = 120.293 (IN-LB)

TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS...
KINETIC ENERGY OF RING = 94.428 (IN-LB)
ELASTIC ENERGY = 21.445 (IN-LB)
DAMPING ENERGY = 0.0 (IN-LB)
PLASTIC WORK = 4.420 (IN-LB)

THE FORCE RESULTANT ACTING ON THE RING DURING THIS CYCLE IS 4749.9922

I	V	W	N	M	EPSI	EPSE	YIELD
1	0.32005709	-7.33051586	-0.00084	-0.00000	-0.00000000	0.00000000	
2	0.95773494	-7.27472687	0.00101	-0.00000	-0.00000000	0.00000000	
3	1.58812428	-7.16357231	0.01179	-0.00002	-0.00000000	0.00000000	
4	2.20642662	-6.99789810	0.09557	-0.00011	-0.00000000	0.00000000	
5	2.80793762	-6.77896500	0.58792	-0.00056	0.00000026	0.00000030	
6	3.38807964	-6.50844002	2.80261	-0.00221	0.00000205	0.00000223	
7	3.94243813	-6.18837833	10.47890	-0.00692	0.00000782	0.00000838	
8	4.46675574	-5.82121277	30.94925	-0.01735	0.00002369	0.00002511	
9	4.95718098	-5.40972614	72.57100	-0.03512	0.00005629	0.00005917	
10	5.40984631	-4.95703220	136.15202	-0.05826	0.00010609	0.00011087	
11	5.82134628	-4.46657467	208.34669	-0.08181	0.00016286	0.00016956	
12	6.18853664	-3.94207764	271.72314	-0.10275	0.00021275	0.00022117	
13	6.50860214	-3.38754177	324.64087	-0.12297	0.00025392	0.00026399	
14	6.77910423	-2.80717850	378.96899	-0.14504	0.00029668	0.00030857	
15	6.99796772	-2.20541000	437.28711	-0.16849	0.00034219	0.00035599	
16	7.16351509	-1.58681393	493.27954	-0.19282	0.00038607	0.00040187	
17	7.27447128	-0.95611405	549.08228	-0.21926	0.00042941	0.0004473[illegible]	
18	7.32997990	-0.31810212	608.59937	-0.24807	0.00047581	0.00049613	
19	7.32960224	0.32240444	669.93335	-0.27990	0.00052358	0.00054651	
20	7.27332687	0.96041393	734.02148	-0.31480	0.00057345	0.00059924	
21	7.16157532	1.59110260	802.48682	-0.35372	0.00062633	0.00065531	
22	6.99516869	2.20967102	875.67236	-0.39705	0.00068341	0.00071593	
23	6.77538109	2.81138229	954.22363	-0.44530	0.00074400	0.00078048	
24	6.50385169	3.39163589	1039.11255	-0.49946	0.00080957	0.00085049	
25	6.18264961	3.94599247	1131.81494	-0.55986	0.00088113	0.00092699	
26	5.81419373	4.47020626	1231.96753	-0.62765	0.00095871	0.00101013	
27	5.40129185	4.96024227	1342.27222	-0.70429	0.00104356	0.00110126	
28	4.94707394	5.41234016	1462.37891	-0.78862	0.00113583	0.00120044	
29	4.45499134	5.82300663	1594.21753	-0.85313	0.00123878	0.00130867	
30	3.92879391	6.18907928	1739.22974	-0.93079	0.00135191	0.00142815	
31	3.37250614	6.50772190	1897.55664	-1.75125	0.00144475	0.00158821	
32	2.79028034	6.77627563	2072.47949	-3.61981	0.00150789	0.00180442	
33	2.18644428	6.99217987	2264.52100	2.93762	0.00193031	0.00168966	
34	1.56618118	7.15543079	2481.14819	34.58766	0.00339979	0.00056637	
35	0.93558884	7.27317810	2715.98975	62.31001	0.00472339	-0.00038104	
36	0.29891807	7.35218620	2776.57031	1.90323	0.00229774	0.00214183	
37	-0.34166980	7.37590122	1721.31494	-94.45346	-0.00252393	0.00531795	*
38	-0.97928584	7.31809235	229.63428	-87.62271	-0.00340699	0.00377107	
39	-1.60436153	7.18195248	-758.90796	38.64862	0.00097454	-0.00219156	
40	-2.21816444	7.00179386	-833.99243	45.50241	0.00119512	-0.00253244	
41	-2.81828022	6.78023243	-794.05493	8.92764	-0.00027095	-0.00100231	
42	-3.39783573	6.50937271	-757.37866	-2.15041	-0.00069557	-0.00051940	
43	-3.95130825	6.18852139	-720.39551	-0.45809	-0.00059636	-0.00055883	
44	-4.47465134	5.82054806	-683.69019	0.51896	-0.00052682	-0.00056933	
45	-4.96403790	5.40844872	-651.23853	0.46770	-0.00050341	-0.00054172	
46	-5.41574478	4.95534801	-620.89185	0.38540	-0.00048201	-0.00051358	
47	-5.82632923	4.46465778	-593.13745	0.34966	-0.00046150	-0.00049014	
48	-6.19266796	3.94009113	-567.84106	0.32010	-0.00044260	-0.00046882	
49	-6.51197243	3.38563251	-543.66357	0.29256	-0.00042417	-0.00044814	
50	-6.78181934	2.80546951	-522.09229	0.26760	-0.00040787	-0.00042980	
51	-7.00014114	2.20401764	-501.03369	0.24506	-0.00039194	-0.00041202	
52	-7.16528130	1.58583069	-481.40601	0.22482	-0.00037676	-0.00039517	
53	-7.27597332	0.95561200	-462.76001	0.20645	-0.00036252	-0.00037943	
54	-7.33137703	0.31813151	-444.03394	0.18945	-0.00034841	-0.00036393	
55	-7.33105373	-0.32181412	-425.54590	0.17439	-0.00033422	-0.00034850	
56	-7.27500725	-0.95925653	-407.30737	0.16013	-0.00032009	-0.00033321	
57	-7.16365814	-1.58940125	-387.41162	0.14663	-0.00030463	-0.00031664	
58	-6.99784565	-2.20746994	-366.02002	0.13406	-0.00028810	-0.00029908	
59	-6.77882957	-2.80875778	-344.86426	0.12183	-0.00027156	-0.00028154	
60	-6.50826359	-3.38869476	-319.45264	0.10893	-0.00025179	-0.00026[illegible]2	
61	-6.18819809	-3.94286919	-288.66089	0.09612	-0.00022773	-0.00023561	
62	-5.82106209	-4.46707247	-258.87744	0.08375	-0.00020431	-0.00021117	
63	-5.40964659	-4.95731068	-226.22411	0.06904	-0.00017865	-0.00018431	
64	-4.95706272	-5.40985584	-178.64011	0.05026	-0.00014125	-0.00014536	
65	-4.46674252	-5.82126331	-118.50880	0.03063	-0.00009400	-0.00009651	
66	-3.94241428	-6.18839550	-63.51056	0.01518	-0.00005059	-0.00005184	
67	-3.38807106	-6.50844383	-27.08475	0.00605	-0.00002173	-0.00002222	
68	-2.80793381	-6.77896595	-9.14327	0.00193	-0.00000746	-0.00000762	
69	-2.20642567	-6.99789810	-2.43418	0.00049	-0.00000212	-0.00000216	
70	-1.58812428	-7.16357231	-0.50782	0.00010	-0.00000055	-0.00000056	
71	-0.95773488	-7.27472687	-0.08204	0.00002	-0.00000019	-0.00000019	
72	-0.32005709	-7.33051586	-0.01006	0.00000	-0.00000009	-0.00000009	

J= 40 TIME= 0.0001000 SEPARATION (IN.) = 14.68608

TOTAL ENERGY INPUT INTO RING = 144.290 (IN-LB)
INITIAL ELASTIC ENERGY = 0.0 (IN-LB)
IMPULSIVE ENERGY INPUT = 0.0 (IN-LB)
EXTERNAL FORCE INPUT = 144.290 (IN-LB)

TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS...
KINETIC ENERGY OF RING = 113.877 (IN-LB)
ELASTIC ENERGY = 24.674 (IN-LB)
DAMPING ENERGY = 0.0 (IN-LB)
PLASTIC WORK = 5.740 (IN-LB)

THE FORCE RESULTANT ACTING ON THE RING DURING THIS CYCLE IS 4999.9922

I	V	W	N	M	EPSI	EPSE	YIELD
1	0.32005709	-7.33051586	-0.03397	-0.00000	-0.00000009	-0.00000009	
2	0.95773494	-7.27472687	0.04130	-0.00006	-0.00000000	0.00000000	
3	1.58812428	-7.16357231	0.30051	-0.00031	0.00000017	0.00000020	
4	2.20642662	-6.99789619	1.53898	-0.00129	0.00000097	0.00000108	
5	2.80793953	-6.77896214	6.21164	-0.00436	0.00000448	0.00000483	
6	3.38808918	-6.50843334	19.92844	-0.01188	0.00001525	0.00001622	
7	3.94246387	-6.18835640	51.04019	-0.02619	0.00003943	0.00004158	
8	4.46685123	-5.82116222	104.84166	-0.04716	0.00008150	0.00008536	
9	4.95726109	-5.40962791	174.63293	-0.07086	0.00013631	0.00014211	
10	5.40994644	-4.95687771	242.66620	-0.09266	0.00018979	0.00019738	
11	5.82144833	-4.46636200	297.89575	-0.11216	0.00023313	0.00024232	
12	6.19862534	-3.94180679	347.91162	-0.13242	0.00027234	0.00028319	
13	6.50866508	-3.38721085	402.54321	-0.15457	0.00031492	0.00032758	
14	6.77912998	-2.80678558	457.79199	-0.17749	0.00035830	0.00037284	
15	6.99794006	-2.20495796	509.92163	-0.20159	0.00039884	0.00041536	
16	7.16342163	-1.58630657	564.17407	-0.22810	0.00044124	0.00045993	
17	7.27429676	-0.95555580	621.40137	-0.25712	0.00048559	0.00050665	
18	7.32971191	-0.31749904	679.81030	-0.28855	0.00053095	0.00055459	
19	7.32922459	0.32304412	741.70117	-0.32398	0.00057904	0.00060558	
20	7.27282715	0.96108061	807.78149	-0.36299	0.00063033	0.00066007	
21	7.16093636	1.59178352	878.40552	-0.40655	0.00068479	0.00071809	
22	6.99437714	2.21035290	954.32959	-0.45521	0.00074388	0.00078117	
23	6.77442074	2.81204700	1036.83398	-0.50958	0.00080739	0.00084914	
24	6.50270844	3.39226437	1126.56567	-0.57053	0.00087650	0.00092324	
25	6.18131065	3.94656181	1223.96045	-0.63860	0.00095156	0.00100387	
26	5.81264400	4.47069073	1331.33765	-0.71500	0.00103456	0.00109313	
27	5.39951992	4.96061039	1447.92358	-0.80165	0.00112403	0.00118970	
28	4.94507027	5.41255760	1576.69873	-0.89534	0.00122281	0.00129615	
29	4.45274734	5.82303429	1717.50293	-0.95586	0.00133319	0.00141149	
30	3.92630672	6.18887711	1872.27905	-1.06047	0.00145293	0.00153980	
31	3.36977482	6.50724220	2042.52734	-2.18748	0.00154281	0.00172201	
32	2.78727531	6.77539444	2228.68848	-4.25131	0.00160689	0.00195516	
33	2.18313885	6.99071693	2435.98584	4.70450	0.00213974	0.00175435	
34	1.56274128	7.15382290	2662.60034	41.09193	0.00381128	0.00044503	
35	0.93233860	7.27313805	2853.68994	66.22298	0.00516717	-0.00050263	*
36	0.29602337	7.35556221	2918.26392	1.52272	0.00239548	0.00227073	
37	-0.34458596	7.38260937	1827.54956	-98.04655	-0.00279343	0.00605322	*
38	-0.98220855	7.32483101	237.04834	-99.97415	-0.00390704	0.00428285	
39	-1.60658360	7.18548107	-751.27002	40.75525	0.00106688	-0.00227180	
40	-2.21962452	7.00271320	-821.44067	53.04149	0.00151379	-0.00283138	
41	-2.81950569	6.78049660	-780.42847	11.73773	-0.00014505	-0.00110661	
42	-3.39909077	6.50968742	-746.61206	-2.60373	-0.00070566	-0.00049236	
43	-3.95253658	6.18877792	-709.23828	-0.80206	-0.00060160	-0.00053590	
44	-4.47579479	5.82067490	-674.00439	0.55740	-0.00051761	-0.00056327	
45	-4.96509171	5.40846062	-641.41577	0.52846	-0.00049319	-0.00053648	
46	-5.41670990	4.95526600	-611.97803	0.42142	-0.00047355	-0.00050807	
47	-5.82720470	4.46449566	-585.27295	0.38028	-0.00045410	-0.00048525	
48	-6.19345474	3.93986225	-560.13940	0.34861	-0.00043528	-0.00046384	
49	-6.51267147	3.38534927	-538.02051	0.31862	-0.00041863	-0.00044474	
50	-6.78243160	2.80514336	-516.64819	0.29126	-0.00040271	-0.00042657	
51	-7.00066948	2.20365906	-497.64624	0.26677	-0.00038845	-0.00041030	
52	-7.16572857	1.58545017	-479.64722	0.24466	-0.00037464	-0.00039468	
53	-7.27634239	0.95521802	-462.45142	0.22477	-0.00036158	-0.00037999	
54	-7.33167171	0.31773239	-446.56055	0.20654	-0.00034985	-0.00036677	
55	-7.33127880	-0.32221037	-430.81006	0.19040	-0.00033785	-0.00035344	
56	-7.27516842	-0.95964319	-414.89868	0.17540	-0.00032570	-0.00034007	
57	-7.16376019	-1.58977032	-399.39648	0.16175	-0.00031369	-0.00032694	
58	-6.99789524	-2.20781612	-383.14111	0.14884	-0.00030128	-0.00031347	
59	-6.77883244	-2.80907631	-364.49487	0.13664	-0.00028679	-0.00029798	
60	-6.50822735	-3.38897991	-345.87891	0.12523	-0.00027236	-0.00028261	
61	-6.18813324	-3.94311619	-325.58472	0.11340	-0.00025664	-0.00026593	
62	-5.82097530	-4.46727848	-298.75586	0.10101	-0.00023554	-0.00024382	
63	-5.40954781	-4.95747757	-269.97266	0.08926	-0.00021284	-0.00022015	
64	-4.95696545	-5.40997791	-242.30272	0.07677	-0.00019119	-0.00019748	
65	-4.46666431	-5.82133961	-204.98573	0.06045	-0.00016206	-0.00016701	
66	-3.94236374	-6.18843460	-150.86749	0.04090	-0.00011947	-0.00012282	
67	-3.38804531	-6.50845909	-91.50746	0.02288	-0.00007272	-0.00007459	
68	-2.80792332	-6.77896976	-44.67644	0.01040	-0.00003561	-0.00003646	
69	-2.20642185	-6.99789810	-17.42247	0.00381	-0.00001400	-0.00001431	
70	-1.58812237	-7.16357231	-5.41178	0.00112	-0.00000452	-0.00000461	
71	-0.95773470	-7.27472687	-1.33449	0.00026	-0.00000129	-0.00000131	
72	-0.32005703	-7.33051586	-0.25903	0.00005	-0.00000037	-0.00000037	

J= 80 TIME= 0.0002000 SEPARATION (IN.) [illegible].81531

TOTAL ENERGY INPUT INTO RING = 1857.894 (IN-LB)
INITIAL ELASTIC ENERGY = 0.0 (IN-LB)
IMPULSIVE ENERGY INPUT = 0.0 (IN-LB)
EXTERNAL FORCE INPUT = 1857.894 (IN-LB)

TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS...
KINETIC ENERGY OF RING = 1492.476 (IN-LB)
ELASTIC ENERGY = 106.823 (IN-LB)
DAMPING ENERGY = 0.0 (IN-LB)
PLASTIC WORK = 258.595 (IN-LB)

THE FORCE RESULTANT ACTING ON THE RING DURING THIS CYCLE IS 9999.9844

I	V	W	N	M	EPSI	EPSE	YIELD
1	0.32950068	-7.32770157	494.28540	-0.30339	0.00038071	0.00040556	
2	0.96728820	-7.27018738	511.56226	-0.35701	0.00039294	0.00042219	
3	1.59760571	-7.15720367	524.20874	-0.41090	0.00040070	0.00043436	
4	2.21566772	-6.98960590	527.02295	-0.46513	0.00040062	0.00043872	
5	2.81673050	-6.76866150	522.61987	-0.52367	0.00039422	0.00043712	
6	3.39619064	-6.49604607	529.76367	-0.59315	0.00039724	0.00044583	
7	3.94961834	-6.17381477	566.20557	-0.67520	0.00042330	0.00047862	
8	4.47277927	-5.80441093	620.22778	-0.76353	0.00046242	0.00052497	
9	4.96163654	-5.39064884	663.69727	-0.85389	0.00049346	0.00056341	
10	5.41241837	-4.93567467	694.50269	-0.94942	0.00051459	0.00059237	
11	5.82164478	-4.44297314	730.02295	-1.05149	0.00053881	0.00062495	
12	6.18615627	-3.91629982	756.23633	-1.15876	0.00055509	0.00065001	
13	6.50310421	-3.35971165	773.63892	-1.28214	0.00056391	0.00066894	
14	6.77003574	-2.77743912	842.84253	-1.43179	0.00061318	0.00073047	
15	6.98486614	-2.17393589	957.00610	-1.60023	0.00069735	0.00082844	
16	7.14587688	-1.55383587	1072.25415	-1.78737	0.00078205	0.00092848	
17	7.25177097	-0.92193109	1225.88306	-1.99430	0.00089649	0.00105987	
18	7.30165291	-0.28305912	1377.60156	-2.20667	0.00100912	0.00118990	
19	7.29506779	0.35782284	1471.80078	-2.43126	0.00107535	0.00127452	
20	7.23200226	0.99563628	1586.33569	-2.68063	0.00115620	0.00137580	
21	7.11286449	1.62543297	1720.36011	-2.95944	0.00125196	0.00149439	
22	6.93849945	2.24234486	1885.25977	-3.27876	0.00137129	0.00163988	
23	6.71016598	2.84150696	2128.06030	-3.63535	0.00155064	0.00184845	
24	6.42953587	3.41818810	2388.48022	-4.04848	0.00174146	0.00207311	
25	6.09870434	3.96778679	2690.56616	-4.58012	0.00196142	0.00233662	
26	5.72013664	4.48586369	2985.37598	-4.94431	0.00218282	0.00258786	
27	5.29677668	4.96819401	3242.20874	-4.30063	0.00241395	0.00276626	
28	4.83211231	5.41103458	3459.80566	-4.98282	0.00255995	0.00296814	
29	4.32968903	5.81070614	3669.58154	-14.18559	0.00235089	0.00351297	
30	3.79212761	6.16195297	3936.14673	-19.11870	0.00236281	0.00392901	
31	3.22346306	6.46053028	4217.83594	9.30936	0.00375191	0.00298929	
32	2.63159370	6.71085358	4549.69922	28.96283	0.00569391	0.00211476	*
33	2.02258492	6.92026043	4914.60937	24.94583	0.01054436	0.00159754	*
34	1.40308189	7.10494423	5336.51172	14.35083	0.01814659	0.00158051	*
35	0.77936816	7.28920269	5737.53125	7.40865	0.02633966	0.00550216	*
36	0.15253496	7.48760700	6130.00781	1.25610	0.02846773	0.02493482	*
37	-0.47908491	7.64043522	4190.64453	-84.93860	-0.00582757	0.03517780	*
38	-1.12116146	7.60206223	1012.89502	-166.16837	-0.02053947	0.03023858	*
39	-1.70896530	7.34874630	-717.91528	78.54784	0.00263992	-0.00379474	
40	-2.28171253	7.06409645	-801.19873	153.80598	0.00943492	-0.01193265	*
41	-2.86058426	6.79218960	-690.38940	138.97037	0.00574277	-0.00771980	*
42	-3.4 460846	6.50959778	-591.95557	70.07423	0.00239312	-0.00334737	
43	-3.99136353	6.19425774	-512.69800	-16.70767	-0.00109787	0.00027082	
44	-4.51599789	5.82788944	-427.35669	-25.27875	-0.00138032	0.00069052	
45	-5.00223936	5.41198254	-377.51270	-1.72994	-0.00037618	-0.00023447	
46	-5.45025921	4.95495033	-348.80005	5.38834	-0.00006134	-0.00050275	
47	-5.85778141	4.46149921	-280.56689	2.61171	-0.00012088	-0.00033483	
48	-6.22134686	3.93477154	-181.62064	1.13928	-0.00010176	-0.00019509	
49	-6.53790855	3.37848568	-113.26431	1.14095	-0.00004694	-0.00014041	
50	-6.80507755	2.79681683	-41.57414	1.13357	0.00001021	-0.00008265	
51	-7.02084064	2.19412041	88.70355	0.99732	0.00010845	0.00002675	
52	-7.18352509	1.57492542	192.19679	0.87795	0.00018727	0.00011535	
53	-7.29186153	0.94395876	221.80371	0.78380	0.00020670	0.00014249	
54	-7.34500217	0.30592215	263.52417	0.69666	0.00023665	0.00017958	
55	-7.34251595	-0.33438385	291.86206	0.62661	0.00025631	0.00020498	
56	-7.28441048	-0.97198504	260.85059	0.56694	0.00022910	0.00018266	
57	-7.17109966	-1.60209465	255.57756	0.50618	0.00022251	0.00018105	
58	-7.00343227	-2.21999836	256.42505	0.45360	0.00022111	0.00018395	
59	-6.78267288	-2.82095623	224.73770	0.40192	0.00019366	0.00016074	
60	-6.51047134	-3.40044403	241.92419	0.33920	0.00020487	0.00017709	
61	-6.18886089	-3.95407009	294.58643	0.28265	0.00024455	0.00022140	
62	-5.82028103	-4.47760105	290.25537	0.24215	0.00023991	0.00022008	
63	-5.40754509	-4.96705246	260.11279	0.20026	0.00021417	0.00019777	
64	-4.95374489	-5.41871166	274.80444	0.14863	0.00022351	0.00021134	
65	-4.46232033	-5.82913589	311.85449	0.09733	0.00025112	0.00024314	
66	-3.93700218	-6.19520950	331.64282	0.05120	0.00026496	0.00026077	
67	-3.38177586	-6.51411343	341.88281	0.00516	0.00027174	0.00027131	
68	-2.80066708	-6.78341293	363.87549	-0.04496	0.00028710	0.00029078	
69	-2.19867229	-7.00106144	398.25659	-0.09720	0.00031261	0.00032057	
70	-1.57978249	-7.16536999	430.45166	-0.14867	0.00033592	0.00034810	
71	-0.94891691	-7.27508068	454.91675	-0.19940	0.00035377	0.00037011	
72	-0.31086218	-7.32933331	475.44019	-0.25046	0.00036779	0.00038831	

J= 120 TIME= 0.0003000 SEPARATION (IN.) = 15.00177

TOTAL ENERGY INPUT INTO RING = 5105.672 (IN-LB)
INITIAL ELASTIC ENERGY = 0.0 (IN-LB)
IMPULSIVE ENERGY INPUT = 0.0 (IN-LB)
EXTERNAL FORCE INPUT = 5105.672 (IN-LB)

TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS...
KINETIC ENERGY OF RING = 3856.886 (IN-LB)
ELASTIC ENERGY = 222.289 (IN-LB)
DAMPING ENERGY = 0.0 (IN-LB)
PLASTIC WORK = 1026.497 (IN-LB)

THE FORCE RESULTANT ACTING ON THE RING DURING THIS CYCLE IS 4999.9922

I	V	W	N	M	EPSI	EPSE	YIELD
1	0.35274738	-7.30816078	-55.62312	-1.17581	-0.00009686	-0.00000054	
2	0.98987734	-7.24633598	15.64742	-1.36024	-0.00004668	0.00006475	
3	1.61908817	-7.12886047	15.20720	-1.55387	-0.00005517	0.00007212	
4	2.23562336	-6.95657921	79.94324	-1.77693	-0.00001254	0.00013303	
5	2.83468533	-6.73075199	181.58656	-2.01395	0.00005848	0.00022347	
6	3.41157627	-6.45307827	246.69141	-2.26201	0.00010047	0.00028577	
7	3.96179008	-6.12562656	321.25269	-2.53853	0.00014939	0.00035735	
8	4.48103142	-5.75088501	450.27026	-2.84302	0.00023944	0.00047234	
9	4.96518326	-5.33169556	574.25220	-3.16831	0.00032537	0.00058493	
10	5.41038895	-4.87126064	695.72803	-3.52708	0.00040836	0.00069730	
11	5.81308746	-4.37311077	872.19897	-3.91369	0.00053350	0.00085411	
12	6.17000866	-3.84111691	993.99976	-4.31370	0.00061433	0.00096771	
13	6.47820091	-3.27945805	1066.54468	-4.74280	0.00065476	0.00104330	
14	6.73511791	-2.69251919	1159.17505	-5.21266	0.00070973	0.00113675	
15	6.53859482	-2.08493042	1252.52856	-5.72449	0.00076326	0.00123221	
16	7.08685303	-1.46150780	1353.82715	-6.28367	0.00082136	0.00133612	
17	7.17855644	-0.82727665	1463.76147	-6.91052	0.00088359	0.00144970	
18	7.21277523	-0.18722194	1665.63013	-7.61412	0.00101605	0.00163980	
19	7.18902588	0.45346707	1880.54468	-8.37283	0.00115724	0.00184314	
20	7.10729122	1.08937645	2033.87842	-9.14302	0.00124795	0.00199695	
21	6.96802235	1.71527576	2168.61621	-9.95918	0.00132207	0.00213792	
22	6.77215672	2.32594299	2316.34155	-11.25729	0.00138799	0.00231019	
23	6.52098656	2.91612339	2499.42920	-12.92409	0.00146582	0.00252456	
24	6.21621513	3.48061562	2715.12793	-11.88211	0.00168030	0.00265368	
25	5.86066055	4.01475811	2980.55151	-9.13045	0.00200540	0.00275336	
26	5.45789528	4.51445389	3253.02563	-20.16861	0.00177191	0.00342413	
27	5.00910187	4.97349167	3584.70728	-39.00914	0.00126493	0.00446056	
28	4.51506519	5.38378334	3963.33105	-21.28081	0.00229353	0.00403684	
29	3.98372459	5.74483490	4368.80469	13.59276	0.00404618	0.00293265	
30	3.42446232	6.06156349	4770.67578	20.50050	0.00524450	0.00274202	*
31	2.84169197	6.33651161	5197.71875	12.29036	0.01064941	0.00257264	*
32	2.24333858	6.58591938	5619.64062	6.33748	0.02159299	0.00376817	*
33	1.63454247	6.84250450	6249.36328	5.25922	0.04324841	0.02076560	*
34	1.02382946	7.12009907	5961.79297	-5.44066	0.05744817	0.03804675	
35	0.40428656	7.41069221	5833.06250	-12.51514	0.07594258	0.06146555	
36	-0.22033840	7.69360447	5564.54687	20.13791	0.07850581	0.06281519	
37	-0.81695563	7.95886898	4001.01123	65.49899	0.00413848	0.03401323	*
38	-1.45880032	8.07457066	1643.81372	-182.24188	-0.05553034	0.09188229	*
39	-1.96419811	7.67993259	275.33252	-137.97357	-0.00565737	0.00640472	*
40	-2.40746117	7.21275806	241.21753	149.63805	0.03076001	-0.02232280	
41	-2.92639828	6.83605671	203.72729	169.41000	0.01974609	-0.01739231	*
42	-3.48048210	6.51504421	193.37378	136.87314	0.00631472	-0.00568713	
43	-4.02602673	6.17987347	294.28564	78.14577	0.00343094	-0.00297077	
44	-4.55257320	5.81546021	453.57422	23.22545	0.00130972	-0.00059291	
45	-5.04934216	5.41132164	523.83154	-45.60184	-0.00145424	0.00228147	
46	-5.50038910	4.95673370	528.11475	-45.35266	-0.00144011	0.00227518	
47	-5.90066338	4.45684052	549.50854	3.85763	0.00059220	0.00027619	
48	-6.25672054	3.92451668	607.36426	18.32788	0.00123175	-0.00026968	
49	-6.56935652	3.36554527	699.13989	5.53191	0.00078091	0.00032773	
50	-6.83346462	2.78201199	778.70752	-0.50944	0.00059742	0.00063915	
51	-7.04558372	2.17762947	816.84326	0.94139	0.00068664	0.00060953	
52	-7.20445442	1.55712986	788.78442	1.90257	0.00070497	0.00054911	
53	-7.30914783	0.92529762	732.75195	1.60168	0.00064711	0.00051590	
54	-7.35879707	0.28673792	733.86206	1.26902	0.00063470	0.00053074	
55	-7.35294247	-0.35379148	775.03882	1.08834	0.00065989	0.00057073	
56	-7.29158020	-0.99137926	827.59473	0.92186	0.00069525	0.00061973	
57	-7.17511559	-1.62123489	905.21289	0.75705	0.00075079	0.00068878	
58	-7.00438576	-2.23864269	909.67627	0.62590	0.00074924	0.00069796	
59	-6.78067875	-2.83383476	812.01660	0.51159	0.00066625	0.00062434	
60	-6.50565243	-3.41727161	749.62402	0.38963	0.00061134	0.00057942	
61	-6.18134689	-3.96958160	722.72729	0.27114	0.00058479	0.00056258	
62	-5.81021214	-4.49153423	658.65161	0.15764	0.00052958	0.00051667	
63	-5.39505863	-4.97917652	613.22583	0.03607	0.00048810	0.00048514	
64	-4.93898678	-5.42877483	602.97192	-0.08100	0.00047464	0.00048128	
65	-4.44548035	-5.83687401	532.17822	-0.17752	0.00041426	0.00042981	
66	-3.91831398	-6.20033932	396.97241	-0.26499	0.00030248	0.00032419	
67	-3.36149311	-6.51637840	265.47705	-0.35448	0.00019406	0.00022310	
68	-2.77928352	-6.78255939	129.48865	-0.44732	0.00008131	0.00011796	
69	-2.17610264	-6.99685669	-1.45609	-0.55374	-0.00002780	0.00001756	
70	-1.55654621	-7.15760994	-75.61588	-0.67621	-0.00009213	-0.00003674	
71	-0.92536265	-7.26357460	-134.61035	-0.81330	-0.00014468	-0.00007805	
72	-0.28730839	-7.31389809	-152.49480	-0.98300	-0.00016653	-0.00008600	

J= 160 TIME= 0.0004000 SEPARATION (IN.) = 15.13294

TOTAL ENERGY INPUT INTO RING = 6092.492 (IN-LB)
  INITIAL ELASTIC ENERGY = 0.0 (IN-LB)
  IMPULSIVE ENERGY INPUT = 0.0 (IN-LB)
  EXTERNAL FORCE INPUT = 6092.492 (IN-LB)

TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS...
  KINETIC ENERGY OF RING = 4821.461 (IN-LB)
  ELASTIC ENERGY = 154.692 (IN-LB)
  DAMPING ENERGY = 0.0 (IN-LB)
  PLASTIC WORK = 1116.336 (IN-LB)

NO FORCE ACTING DURING THIS CYCLE

I	V	W	N	M	EPSI	EPSE	YIELD
1	0.38926601	-7.26939106	-151.40341	-3.25335	-0.00026036	0.00000616	
2	1.02567005	-7.20056534	22.06512	-3.68490	-0.00013846	0.00016341	
3	1.65350819	-7.07554722	182.92386	-4.13840	-0.00002835	0.00031067	
4	2.26785374	-6.89520168	312.61035	-4.60900	0.00005574	0.00043331	
5	2.86374569	-6.66082573	386.77295	-5.08560	0.00009525	0.00051186	
6	3.43630028	-6.37420368	346.30249	-5.56736	0.00004293	0.00049901	
7	3.98084736	-6.03751755	215.15981	-6.06387	-0.00008161	0.00041515	
8	4.49293232	-5.65342236	3.09447	-6.59070	-0.00027350	0.00026642	
9	4.96831608	-5.22492123	-217.11798	-7.18069	-0.00047403	0.00011423	
10	5.40309334	-4.75534725	-348.01538	-7.85865	-0.00060599	0.00003780	
11	5.79359818	-4.24838352	-378.89282	-8.61764	-0.00066166	0.00004430	
12	6.13649273	-3.70808220	-401.78223	-9.44461	-0.00071415	0.00005955	
13	6.42872143	-3.13881207	-433.76855	-10.33107	-0.00077607	0.00007025	
14	6.66763306	-2.54524708	-535.61865	-11.30245	-0.00089724	0.00002866	
15	6.85100460	-1.93223190	-529.75562	-12.41787	-0.00093845	0.00007881	
16	6.97699451	-1.30481529	-359.27759	-13.65055	-0.00085272	0.00026553	
17	7.04418564	-0.66852421	-476.78638	-14.86520	-0.00099633	0.00022142	
18	7.05165863	-0.02880001	-706.29517	-15.89177	-0.00122247	0.00007938	
19	6.99908829	0.60893244	-556.26831	-17.49057	-0.00116728	0.00026554	
20	6.88649654	1.23888397	-323.25830	-21.43086	-0.00114253	0.00061308	
21	6.71389435	1.85507679	-414.13647	-23.53491	-0.00130181	0.00062616	
22	6.48233032	2.45162868	-459.92139	-15.60327	-0.00101269	0.00026553	
23	6.19584084	3.02402020	-127.51463	-14.86518	-0.00071689	0.00050086	
24	5.85715580	3.56715202	-153.36157	-45.15813	-0.00197910	0.00172024	
25	5.46288490	4.07123470	-433.91040	-62.35156	-0.00290767	0.00220017	
26	5.01402473	4.52751732	-330.71533	-32.02103	-0.00158255	0.00104062	
27	4.52160549	4.93636036	-391.47339	-7.66335	-0.00063374	-0.00000597	
28	3.99425507	5.29904079	-392.70459	16.30017	0.00034632	-0.00098900	
29	3.43947124	5.61815834	-372.99780	84.89656	0.00317167	-0.00378307	
30	2.86890984	5.90824223	-315.38501	141.09329	0.00761350	-0.00798782	*
31	2.29447269	6.19497013	-408.44849	136.32152	0.01443325	-0.00860775	*
32	1.72438717	6.50174999	-147.69019	49.14281	0.02293551	-0.00052780	
33	1.15577412	6.83222294	-360.89502	-44.90500	0.03633588	0.01791682	
34	0.58071816	7.17179680	-58.67334	-52.74855	0.05069214	0.03516643	
35	-0.00864761	7.51355934	-148.88965	49.27116	0.07368565	0.05414736	
36	-0.59508908	7.86354733	5.41724	82.11481	0.07660377	0.05580660	
37	-1.14782906	8.20789146	-11.37315	-65.94614	[illegible]	0.03579462	
38	-1.77508259	8.38156128	-113.10791	-195.90993	[illegible]	0.10150915	*
39	-2.26778698	7.97303963	-285.65112	-171.67514	-0.02133803	0.01836932	*
40	-2.62542439	7.43760204	-169.08641	-6.63721	0.02402923	-0.01625128	
41	-3.04198551	6.94987297	-170.97168	60.02342	0.02408839	-0.02271382	
42	-3.52636051	6.53182507	-212.40747	171.64026	0.01760545	-0.01958025	*
43	-4.05133915	6.16570187	-146.49854	137.42015	0.00559866	-0.00598155	*
44	-4.56587696	5.78505230	-175.06738	86.55859	0.00339925	-0.00369164	
45	-5.06034184	5.37868595	-209.95103	20.45738	0.00066288	-0.00101299	
46	-5.52131462	4.93475056	-273.75317	-25.82167	-0.00128319	0.00083213	
47	-5.93656254	4.44781685	-352.24219	-60.57312	-0.00276965	0.00219252	
48	-6.29442596	3.91727924	-327.40112	-48.68735	-0.00226269	0.00172578	
49	-6.59320068	3.35136414	-325.64087	16.48689	0.00040816	-0.00094246	
50	-6.84558296	2.76328564	-345.21387	37.32794	0.00124635	-0.00181156	
51	-7.05524731	2.15865803	-310.49390	7.53545	0.00005333	-0.00056398	
52	-7.21337986	1.53853512	-279.21460	-7.59158	-0.00053964	0.00008226	
53	-7.31485844	0.90669560	-234.95667	[illegible]	-0.00023990	-0.00014895	
54	-7.36058140	0.26829481	-147.52223	3.35706	0.00001348	-0.00026154	
55	-7.35138988	-0.37174678	-96.41370	2.17349	0.00000569	-0.00017236	
56	-7.28703308	-1.00857449	-66.36404	0.92940	-0.00002152	-0.00009766	
57	-7.16765881	-1.63738823	-17.96436	0.73414	0.00000968	-0.00005046	
58	-6.99411011	-2.25354004	24.64771	0.63305	0.00003980	-0.00001206	
59	-6.76767540	-2.85229969	61.21812	0.39809	0.00005914	0.00002653	
60	-6.49001503	-3.42909431	71.99651	0.15640	0.00005799	0.00004518	
61	-6.16317368	-3.97950840	54.67754	-0.06452	0.00003470	0.00003998	
62	-5.78958988	-4.49931812	39.10117	-0.27875	0.00001428	0.00003712	
63	-5.37209225	-4.98454094	-7.73964	-0.48453	-0.00003195	0.00000774	
64	-4.91383076	-5.43139744	-91.63907	-0.69262	-0.00010733	-0.00005059	
65	-4.41827011	-5.83644485	-147.57294	-0.91729	-0.00016188	-0.00008674	
66	-3.88916206	-6.19657040	-168.31000	-1.15171	-0.00018796	-0.00009362	
67	-3.33054161	-6.50891876	-206.60153	-1.39915	-0.00022790	-0.00011328	
68	-2.74667835	-6.77104855	-198.86687	-1.67659	-0.00023330	-0.00009595	
69	-2.14199543	-6.98088646	-114.94193	-1.96819	-0.00017820	-0.00001697	
70	-1.52118778	-7.13671207	-91.82127	-2.25381	-0.00017156	0.00001307	
71	-0.88912898	-7.23723793	-131.96915	-2.54433	0.00021512	-0.00000669	
72	-0.25064856	-7.28160572	-184.43657	-2.86807	-0.00027084	-0.00003588	

J= 200 TIME= 0.0005000 SEPARATION (IN.) = 15.31368

TOTAL ENERGY INPUT INTO RING = 6092.492 (IN-LB)
INITIAL ELASTIC ENERGY = 0.0 (IN-LB)
IMPULSIVE ENERGY INPUT = 0.0 (IN-LB)
EXTERNAL FORCE INPUT = 6092.492 (IN-LB)

TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS...
KINETIC ENERGY OF RING = 4731.012 (IN-LB)
ELASTIC ENERGY = 193.938 (IN-LB)
DAMPING ENERGY = 0.0 (IN-LB)
PLASTIC WORK = 1167.539 (IN-LB)

NO FORCE ACTING DURING THIS CYCLE

I	V	W	N	M	EPSI	EPSE	YIELD
1	0.42798162	-7.23269272	1008.15259	-5.52803	0.00057241	0.00102527	
2	1.06401157	-7.15646553	967.47949	-6.09734	0.00051743	0.00101693	
3	1.69061565	-7.02349567	946.87622	-6.74228	0.00047425	0.00102659	
4	2.30282879	-6.83466530	1093.47705	-7.42264	0.00056306	0.00117113	
5	2.89547443	-6.59136486	1005.89648	-8.12265	0.00046455	0.00112996	
6	3.46361732	-6.29541683	952.64819	-8.91968	0.00038879	0.00111950	
7	4.00256348	-5.94901562	1070.40723	-9.77499	0.00044855	0.00124932	
8	4.50762272	-5.55492306	964.74707	-10.67603	0.00032681	0.00120140	
9	4.97443390	-5.11623001	936.03931	-11.68060	0.00026257	0.00121946	
10	5.39890862	-4.63642406	955.09790	-12.77885	0.00023295	0.00127980	
11	5.77715778	-4.11941051	934.41772	-13.98524	0.00016744	0.00131310	
12	6.10574436	-3.56940269	1077.22363	-15.27949	0.00022849	0.00148018	
13	6.38145828	-2.99102974	1182.92603	-16.76515	0.00025219	0.00162558	
14	6.60151482	-2.38917732	1352.86182	-18.65642	0.00031086	0.00183918	
15	6.76345825	-1.76908875	1472.16089	-20.22647	0.00034134	0.00199828	
16	6.86536694	-1.13632870	1515.40649	-20.39169	0.00036912	0.00203960	
17	6.90625005	-0.49677110	1552.31079	-22.83911	0.00029895	0.00216992	
18	6.88516045	0.14380914	1532.29370	-31.91708	-0.00008983	0.00252481	
19	6.75976082	0.77908933	1548.76196	-33.50027	-0.00014136	0.00260297	
20	6.65056610	1.40236187	1507.80835	-15.83775	0.00054987	0.00184730	
21	6.44355392	2.00895691	1550.09985	-15.96518	0.00057800	0.00188584	
22	6.18055439	2.59344578	1485.41284	-52.25916	-0.00095936	0.00332170	
23	5.85545826	3.14576054	1371.73120	-68.49393	-0.00171587	0.00389515	
24	5.46866798	3.65667629	1152.51465	-62.49602	-0.00164656	0.00347312	
25	5.02658463	4.12045383	907.12964	-71.63824	-0.00221694	0.00365167	
26	4.53327465	4.52528162	766.89819	-43.65451	-0.00118275	0.00239344	
27	3.99966431	4.88385391	707.09448	41.00749	0.00223688	-0.00112247	
28	3.44260311	5.20015526	594.50342	109.52242	0.00495274	-0.00401935	
29	2.87284851	5.49318695	513.15820	144.70299	0.00914264	-0.00770046	*
30	2.30280685	5.78563213	335.12866	153.13950	0.01429912	-0.01276886	
31	1.74708557	6.10777187	192.53882	75.96294	0.01252148	-0.00580673	
32	1.18891621	6.43624687	329.73926	59.05446	0.02372168	-0.00055340	
33	0.63464655	6.79063034	229.70923	131.78172	0.04427144	0.01059676	*
34	0.10430664	7.19701195	387.96094	111.07932	0.05781375	0.02867596	
35	-0.41021836	7.64419174	154.31023	-32.32202	0.07058454	0.05773048	
36	-0.93537247	8.08098412	181.84937	-103.53264	0.06857377	0.06378275	
37	-1.46047974	8.46467400	88.05322	-163.27794	-0.01206852	0.04186496	*
38	-2.08752823	8.63693714	15.45557	-201.61237	-0.07520771	0.10532993	*
39	-2.55911064	8.20420265	7.74097	-177.74033	-0.02615739	0.02318793	*
40	-2.86178112	7.63622475	1.50098	-94.46587	0.01865486	-0.01173172	
41	-3.20097160	7.09152317	102.95613	50.03064	0.02389612	-0.02208726	
42	-3.61565971	6.60358238	-8.94043	145.26640	0.01980350	-0.02072329	
43	-4.08577251	6.16878986	43.00195	165.98505	0.01469432	-0.01457811	*
44	-4.58201122	5.76439190	6.31665	138.77843	0.00580863	-0.00580528	*
45	-5.06678581	5.34636688	-26.13159	74.06754	0.00300401	-0.00306361	
46	-5.52727127	4.90183258	-151.09399	15.07529	0.00048852	-0.00074645	
47	-5.95024872	4.42157078	-319.81860	-35.75529	-0.00172890	0.00120019	
48	-6.32192802	3.90071964	-496.20947	-59.23483	-0.00283141	0.00202112	
49	-6.63293534	3.34169197	-770.14380	-49.52516	-0.00265317	0.00140393	
50	-6.88181973	2.75245571	-949.04175	-25.51366	-0.00181259	0.00027749	
51	-7.07185650	2.14174366	-1016.85962	28.77269	0.00035651	-0.00200056	
52	-7.21548843	1.51844788	-960.17212	50.62477	0.00129868	-0.00284850	
53	-7.31768703	0.88705045	-829.99976	7.61788	-0.00036008	-0.00098414	
54	-7.36649990	0.24922889	-831.55493	-20.19679	-0.00150039	0.00015413	
55	-7.35411549	-0.39036936	-853.54468	-5.28583	-0.00090743	-0.00047441	
56	-7.28463268	-1.02622318	-875.34375	7.42087	-0.00040456	-0.00101248	
57	-7.16194534	-1.65395069	-877.39819	3.88441	-0.00055043	-0.00086865	
58	-6.98599148	-2.26899719	-766.33203	-0.33526	-0.00063453	-0.00060707	
59	-6.75699711	-2.86641407	-616.97168	-0.30186	-0.00051338	-0.00048916	
60	-6.47672462	-3.44157982	-565.63330	0.17278	-0.00045347	-0.00046763	
61	-6.14739037	-3.99020672	-450.13257	-0.22648	-0.00037755	-0.00035900	
62	-5.77133846	-4.50813675	-116.98904	-0.75963	-0.00013168	-0.00006945	
63	-5.35138035	-4.99126625	48.65825	-1.10155	-0.00001402	0.00007622	
64	-4.89072895	-5.43571186	-24.12340	-1.42496	-0.00008500	0.00003174	
65	-4.39279461	-5.83806133	126.34427	-1.83937	0.00001777	0.00016846	
66	-3.86127090	-6.19518185	449.63184	-2.25094	0.00025968	0.00044408	
67	-3.30033207	-6.50408649	492.43359	-2.61465	0.00027989	0.00049408	
68	-2.71435928	-6.76227474	435.10718	-3.03535	0.00021666	0.00046532	
69	-2.10771275	-6.96768093	704.11108	-3.52163	0.00041165	0.00070015	
70	-1.48515606	-7.11853695	897.87329	-3.97388	0.00054779	0.00087334	
71	-0.85176903	-7.21349335	800.15625	-4.43193	0.00045138	0.00081444	
72	-0.21236002	-7.25169659	846.96069	-4.96738	0.00046650	0.00087343	

J= 240 TIME= 0.0006000 SEPARATION (IN.) = 15.42410

TOTAL ENERGY INPUT INTO RING = 6092.492 (IN-LB)
INITIAL ELASTIC ENERGY = 0.0 (IN-LB)
IMPULSIVE ENERGY INPUT = 0.0 (IN-LB)
EXTERNAL FORCE INPUT = 6092.492 (IN-LB)

TOTAL ENERGY IS NOW DISTRIBUTED AS FOLLOWS...
KINETIC ENERGY OF RING = 4662.516 (IN-LB)
ELASTIC ENERGY = 194.327 (IN-LB)
DAMPING ENERGY = 0.0 (IN-LB)
PLASTIC WORK = 1235.648 (IN-LB)

NO FORCE ACTING DURING THIS CYCLE

I	V	W	N	M	EPSI	EPSE	YIELD
1	0.47415276	-7.18206596	-591.59570	-7.66019	-0.00079666	-0.00016913	
2	1.10821819	-7.09706457	-646.44531	-8.47571	-0.00087281	-0.00017847	
3	1.73196697	-6.95491123	-650.31372	-9.34932	-0.00091204	-0.00014613	
4	2.34020042	-6.75654793	-695.80151	-10.28151	-0.00098709	-0.00014482	
5	2.92774105	-6.50340366	-735.23926	-11.28652	-0.00105973	-0.00013513	
6	3.48950863	-6.19736195	-764.44312	-12.38154	-0.00112832	-0.00011403	
7	4.02064800	-5.84073639	-715.52905	-13.58006	-0.00113784	-0.00002536	
8	4.51639175	-5.43635273	-735.33057	-14.91172	-0.00120831	0.00001326	
9	4.97222519	-4.98740959	-640.91138	-16.29077	-0.00118928	0.00014527	
10	5.38393307	-4.49755859	-478.80981	-17.61958	-0.00111446	0.00032893	
11	5.74748611	-3.97096062	-448.14087	-19.60437	-0.00117043	0.00043556	
12	6.05921555	-3.41206360	-364.39844	-22.51395	-0.00122284	0.00062150	
13	6.31551838	-2.82567596	-345.55347	-23.05461	-0.00122971	0.00065891	
14	6.51386070	-2.21722794	-351.67432	-20.59021	-0.00113389	0.00055285	
15	6.65303707	-1.59258747	-367.65308	-27.14354	-0.00141544	0.00080814	
16	6.73000050	-0.95729160	-404.41724	-43.38217	-0.00211010	0.00144376	
17	6.73967075	-0.31752676	-460.04614	-37.42635	-0.00191020	0.00115577	
18	6.68351650	0.31997687	-378.82153	-12.09978	-0.00080847	0.00018274	
19	6.56881428	0.94962633	-404.91431	-22.40419	-0.00125158	0.00058376	
20	6.39390469	1.56512547	-459.09521	-52.10625	-0.00251102	0.00175753	
21	6.15295982	2.15799713	-430.82300	-54.58148	-0.00259005	0.00188126	
22	5.84831810	2.72078323	-525.04224	-74.38136	-0.00347546	0.00261786	
23	5.47930336	3.24362850	-555.99561	-109.66193	-0.00494578	0.00403772	
24	5.04402256	3.71289253	-474.09644	-87.53227	-0.00397520	0.00319545	
25	4.55405331	4.12476254	-533.01440	-28.00476	-0.00158351	0.00071065	
26	4.02572536	4.48620987	-457.32520	32.33014	0.00094862	-0.00169987	
27	3.47222519	4.80778027	-399.08154	107.41261	0.00407009	-0.00472917	
28	2.90568256	5.10566807	-437.53979	131.82607	0.00662002	-0.00731187	
29	2.33398724	5.39469051	-343.40845	96.61920	0.00966275	-0.00852581	
30	1.76422691	5.68694210	-353.32324	137.68007	0.01311576	-0.01268873	
31	1.20649815	6.00539589	-73.71509	147.05487	0.01593257	-0.00953683	*
32	0.65871918	6.35031509	67.87207	164.41512	0.03294322	-0.01078878	*
33	0.15476298	6.77344799	191.13306	97.62276	0.04498963	0.00999049	
34	-0.31548005	7.24813557	224.58740	55.91269	0.05542190	0.03080355	
35	-0.77632117	7.75061226	262.39868	-40.44032	0.07033688	0.05814812	
36	-1.25027466	8.24203682	179.54565	-112.94189	0.06633389	0.06492651	
37	-1.73720074	8.67203045	84.90479	-178.58777	-0.02226827	0.04972025	*
38	-2.36361217	8.84420013	28.90576	-202.46970	-0.08012104	0.10823572	*
39	-2.81757164	8.39307308	-218.87598	-152.85304	-0.02757126	0.02449286	
40	-3.08943844	7.80956268	30.[illegible]523	-110.41893	0.01665929	-0.00914002	
41	-3.38571167	7.24029827	242.44482	-20.33447	0.02112345	-0.01909539	
42	-3.74614525	6.71091652	48.50676	42.29404	0.01562318	-0.01652174	
43	-4.14649010	6.21052647	175.12744	109.55423	0.02056842	-0.01950988	
44	-4.60286045	5.76068497	499.84644	152.48817	0.01211510	-0.01031126	*
45	-5.07119846	5.32380772	503.73657	110.89020	0.00528259	-0.00429352	
46	-5.52247524	4.86938858	584.95850	68.33458	0.00325693	-0.00234104	
47	-5.94641018	4.38924503	741.98291	12.58308	0.00109877	0.00006797	
48	-6.32956600	3.87603283	666.37646	-45.75313	-0.00135103	0.00239709	
49	-6.65601921	3.32504463	623.66064	-68.07883	-0.00229994	0.00327709	
50	-6.91664791	2.73991871	811.25977	-60.71765	-0.00184804	0.00312595	
51	-7.10980225	2.12915516	897.31396	-22.05280	-0.00019569	0.00161087	
52	-7.24319553	1.50267887	775.80518	9.10155	0.00098485	0.00023925	
53	-7.32390690	0.86731333	850.54248	35.63936	0.00213022	-0.00078936	
54	-7.35850239	0.22763300	964.41382	47.44412	0.00270509	-0.00118154	
55	-7.34995270	-0.41291004	868.85645	4.05216	0.00085131	0.00051935	
56	-7.28670025	-1.05029106	861.80078	-33.04565	-0.00067399	0.00203311	
57	-7.15942669	-1.67798424	801.86084	-12.04606	0.00013866	0.00112548	
58	-6.97486496	-2.29116249	467.60522	12.88991	0.00089280	-0.00016314	
59	-6.74082375	-2.88711834	278.15796	7.08189	0.00050275	-0.00007740	
60	-6.45746231	-3.46119690	186.33794	-3.53662	-0.00000556	0.00028416	
61	-6.12436350	-4.00784397	46.44214	-3.43085	-0.00011343	0.00016762	
62	-5.74414825	-4.52281666	23.69458	-0.97204	-0.00002966	0.00004996	
63	-5.32037830	-5.00245476	-170.96484	-1.25572	-0.00014763	-0.00009476	
64	-4.85622787	-5.44304466	-296.99634	-2.32069	-0.00034153	-0.00015142	
65	-4.35507679	-5.84099388	-344.44727	-2.84112	-0.00040140	-0.00016865	
66	-3.82080269	-6.19308090	-520.50391	-3.21772	-0.00055790	-0.00029430	
67	-3.25744152	-6.49650097	-487.67725	-3.73397	-0.00055157	-0.00024568	
68	-2.66940784	-6.74873638	-506.10156	-4.29418	-0.00058979	-0.00023801	
69	-2.06129265	-6.94766426	-575.08618	-4.88061	-0.00066912	-0.00026930	
70	-1.43785191	-7.09155560	-557.96118	-5.49983	-0.00068098	-0.00023043	
71	-0.80415648	-7.17909336	-634.25073	-6.16872	-0.00076918	-0.00026384	
72	-0.16506505	-7.20940876	-599.19263	-6.89827	-0.00077132	-0.00020621	

FIRST YIELDING AT TIME = 0.000092