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Contract AF 29(601)-6776

TECHNICAL REPORT NO. AFWL-TR-67-7

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AIR FORCE WEAPONS LABORATORY
Research and Technology Division
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FOREWORD

This report was prepared by the University of Illinois, Urbana, Illinois, under Contract AF 29(601)-6776. The research was performed under Program Element 6.16.46.01.D, Project 5710, Subtask 13.157, and was funded by the Defense Atomic Support Agency (DASA).

Inclusive dates of research were 15 April 1965 to 23 June 1967. The report was submitted 29 June 1967 by the Air Force Weapons Laboratory Project Officer, Mr. Herbert W. Craig (WLDC).

The authors wish to express their appreciation to the project monitors, Captain Frusti, Mr. Atkinson, and Mr. Craig, for their cooperation and understanding, to Dr. N. N. Nielsen who participated effectively as a member of the project staff, and especially to Dr. A. R. Robinson who, though not a member of the project staff, gave generously of his time in consultation and contributed significantly to development of the computer program, which was the essential element of this project. Acknowledgment is also given to Dr. J. W. Melin for his valuable guidance and counsel.

This technical report has been reviewed and is approved.

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ABSTRACT

(Distribution Limitation Statement No. 2)

This report presents the results of an analytical research effort aimed toward defining the degradation of structural integrity that may result when design conditions are not met during the construction of hardened facilities. Parameters of primary concern were: (a) variations in the soil resistance around a buried structure (nonuniform backfill properties); (b) variations in the structural geometry (improperly enforced construction tolerances); (c) variations in structural material properties. A computer program was developed to study the influence of variations in these parameters by representing the structure-soil system by a lumped-parameter model and solving the resulting equations by numerical integration. The program is restricted to planar reinforced concrete structures, with particular emphasis on buried arches and cylindrical structures. The program considers both elastic and inelastic response of the structure under any combination of axial force and bending. It is also capable of representing a variety of multilinear blast pressure pulses that may approach the structure from any direction in the plane of the structure.

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ILLUSTRATIONS

ABBREVIATIONS AND SYMBOLS

A1	- first pressure amplitude
A2	- second pressure amplitude
A_{EQUIV}	- modified area of compression steel
A_s	- area of steel
DEFYY(I)	- yield deformation of the springs at mass I
E	- modulus of elasticity
E_c	- modulus of elasticity of concrete
$FORCE_{BARi}$	- total internal force in bar i
$FORCE_{xi}^{BLAST}$	- horizontal blast force acting on mass i
$FORCE_{yi}^{BLAST}$	- vertical blast force acting on mass i
$FORCE_{BARi}^{CONC}$	- total force developed by the concrete in bar i
$FORCE_{JTi}^{CONC}$	- total force developed by the concrete in joint i
$FORCE_{xi}^{SPRING}$	- horizontal force on mass i from soil spring
$FORCE_{yi}^{SPRING}$	- vertical force on mass i from soil spring
FORCYY(I)	- yield pressure of the springs at mass I
H	- total depth of cross section
I	- moment of inertia of a section
L	- initial length of all bars
M	- bending moment
MOM_{JTi}	- total internal moment in joint i
MOM_{BARi}^{CONC}	- total moment developed by the concrete in bar i
MOM_{JTi}^{CONC}	- total moment developed by the concrete in joint i

$PLASTIC\ SET_{BAR\,i}^{INNER\ STEEL}$	- plastic set in the inner steel of bar i
$PLASTIC\ SET_{BAR\,i}^{j}$	- plastic set in fiber j of bar i
$PLASTIC\ SET_{BAR\,i}^{OUTER\ STEEL}$	- plastic set in the outer steel of bar i
$PRESSURE_i$	- vertical pressure acting downward on mass i
RATIO	- ratio of horizontal to vertical blast pressures in soil
T(I)	- the elapsed time since wave contact with mass I
TAR2	- time at which second pressure wave, A2, arrives
TR1	- time at which pressure attains amplitude A1
TR2	- time at which pressure attains amplitude A2
$V_{BAR\,i}$	- transverse shear acting at ends of bar i
VERTICAL VELOCITY	- vertical velocity of the wave front
$WAVE\ FRONT^{t=t}$	- location of the wave front at time t
k_i	- soil spring stiffness of springs at mass i
n	- E_s/E_c
n_f	- number of fibers used to represent the cross-section
x_i	- x coordinate of mass i
$\dot{x}_i^{(t)}$	- velocity of mass i in the x direction at the beginning of the time interval; is known either as an initial condition or from analysis of the preceding time interval
$\ddot{x}_i^{(t)}$	- acceleration of mass i in the x direction at the beginning of the time interval; it is known either as an initial condition or from analysis of the preceding time interval.
$\ddot{x}_i^{(t+\Delta t)}$	- acceleration of mass i in the x direction at the end of the time interval.
y_i	- y coordinate of mass i
$\dot{y}_i^{(t)}$	- velocity of mass i in the y direction at the beginning of the time interval; it is known either as an initial condition or from analysis of the preceding time interval

$\ddot{y}_i^{(t)}$	- acceleration of mass i in the y direction at the beginning of the time interval; it is known either as an initial condition or from analysis of the preceding time interval.
$\ddot{y}_i^{(t+\Delta t)}$	- acceleration of mass i in the y direction at the end of the time interval.
$\ddot{z}_i$	- represents either $\ddot{x}_i$ or $\ddot{y}_i$
β	- dimensionless constant used in numerical integration
ΔL_i^{TOTAL}	- total change in length of bar i
$\Delta L_i^{(t+\Delta t)}$	- incremental change in the length of bar i during the time interval Δt
$\Delta x_i^{(t+\Delta t)}$	- displacement of mass i in the x direction during the time interval Δt
Δy	- distance blast wave propagates downward in the time Δt
$\Delta y_i^{(t+\Delta t)}$	- displacement of mass i in the y direction during time interval Δt
$\Delta\alpha_i^{TOTAL}$	- total change in α_i
$\Delta\alpha_i^{(t+\Delta t)}$	- incremental change in α_i during the time interval Δt
$\Delta\rho_i^t$	- total accumulated change in intersection angle between bars i and i-1 to time t
ψ_{BARi}	- curvature at mid-length of bar i
ψ_{JTi}^t	- average curvature in joint i at time t
α_i	- acute angle bar i makes with the horizontal
$\delta_{yi}^{t=t}$	- vertical distance between the wave front and mass i at time t
ϵ_{cr}	- strain at which concrete begins to fail.
ϵ_o	- strain axis intercept
ϵ_u	- ultimate strain or strain at which the concrete crushes
ϵ_y	- initial yield strain
ϵ_{BARi}^{AVG}	- average axial strain in bar i

ϵ_{JTi}^{AVG} - average axial strain in joint i

ϵ_{y}^{CONC} - yield strain in concrete

$\epsilon_{BARi}^{INNER\ STEEL}$ - strain in the inner steel of bar i

ϵ_{BARi}^{j} - strain in fiber j of bar i

ϵ_{JTi}^{j} - strain in fiber j of joint i

$\epsilon_{BARi}^{OUTER\ STEEL}$ - strain in the outer steel of bar i

ϵ_{y}^{STEEL} - yield strain in steel

ϵ_{BARi}^{z} - strain in bar i at some distance z above or below the plastic centroid

ϵ_{JTi}^{z} - strain in joint i at some distance z above or below the plastic centroid

ρ_{i}^{t} - intersection angle between bars i and i-1 at time t

σ_{BARi}^{j} - stress in fiber j of bar i

σ_{JTi}^{j} - stress in fiber j of joint i

SECTION I

INTRODUCTION

1. Objectives:

The basis of the problem considered in this study is an acknowledgment of the fact that significant differences may exist between the conditions assumed for the design of hardened underground structures and the corresponding conditions that actually exist in the as-built structure. Of particular concern are the variations that might exist between the assumed and the real soil resistance characteristics, the geometry or alignment of the structure, and the properties of the structural materials. Hence, the primary objective of this study was to develop a method to investigate the influence of variations in these several significant parameters on the resistance of a buried structure to nuclear blast loading.

A secondary objective of the project was to use the method of analysis thus developed to investigate to a limited extent the influence of variations in some of the more significant parameters on the blast resistance of buried structures.

2. Scope of Effort:

Because a comprehensive study of the problems indicated in the subject of this report is formidable, the scope of the study must be clearly defined. The major effort was to develop an analytical method to study the influence of significant parameter variations on the resistance of buried structures to nuclear blast loads. A secondary effort was to use this method to study the influence of such variations on specific structures.

It is emphasized that the significance of parameter variations on the resistance of buried structures is the primary interest of this study. The research reported here is not intended as a further study of soil-structure interaction or to identify quantitatively the influence of structural deformations on the pressures that exist across a soil-structure interface.

Because of its wide use in protective construction and its probable sensitivity to the effects of parameter variations, the buried reinforced concrete arch was used as the basis structural type in this study. For example, consider a fully buried arch that has been designed on the assumption that the soil resistance around it is uniform at a given level of resistance. These studies relate to the extent to which the resistance of such an arch is reduced if over part of its surface area the soil resistance is reduced by ten percent, fifteen percent, thirty percent, etc., of the basic resistance offered by the soil over the remaining surface area of the arch. Similarly, if an arch is designed on the assumption that it is an arc of a true circle, by what percentage is its resistance reduced if during the construction and backfilling operations variations from the assumed circular shape equal to one percent, two percent, five percent, etc., of the radius are developed?

The method of analysis that was developed is sufficiently general that it can be used directly for the study of any two-dimensional reinforced concrete configuration having a constant cross section. Thus, it is directly applicable to the analysis of cylindrical or rectangular reinforced concrete structures of constant wall thickness. With relatively minor modifications, the method can also be applied to other planar structures of other materials.

The method of analysis that was developed was a computer program capable of solving for the response of a lumped parameter model of the soil-structure systems to blast-induced soil pressures. Response was not restricted to the linearly elastic range; inelastic structural behavior under any combination of axial force and bending can also be considered.

3. Significance of Study:

If properly exploited the computer program developed in this study could yield results of substantial immediate significance not only to the design and construction of hardened facilities in the future but also to the evaluation of the hardness of existing similar facilities. For example, in the design of future facilities, a better understanding of the influence of variations in parameters such as soil resistance, structural material properties, and structural geometry would be of great value to the designer as he proportions a structure to provide a specified level of blast resistance. Considering the uncertainties inherent in these parameters in any design problem, a proper approach is to design the structure to provide a specified probability that the facility will survive, with acceptable damage levels, a given intensity of blast loading. The computer program developed herein can be used effectively to obtain statistical data on the influences of the several parameters on the resistance that would be required for any useful probability analysis.

Similarly, it could be used to provide the input information that would be required for a probabilistic analysis of the blast resistance of in-place structures. It should be possible, for example, to determine for a given in-place facility the extent to which the structural geometry, the structural material properties, and the soil properties differed from the values of these parameters that were used in the design of the facility. On the basis of this information, the computer program could be used to determine the extent to which the actual blast resistance of the facility differs from that for which it was originally designed.

Further, data that can be acquired through the exploitation of this computer program should be especially useful in the preparation of specifications for the construction of hardened facilities in the future. A better understanding of the influences of variations in the several significant parameters on the resistance of the structure is essential in order to specify permissible design and construction tolerances.

SECTION II

METHOD OF STUDY

1. General Discussion of Problem:

An actual structure will inevitably differ from the planned structure and from the idealized structure that was considered in the design. Errors and unforeseen circumstances in the construction can result in marked variations from the conditions specified on the plans which, in turn, may have been simplified and idealized to an appreciable extent to arrive at the design. Variations of this type always exist in any structure but they take on higher than usual importance when considered in regard to underground structures that are designed for high levels of nuclear blast loads.

The principal differences that may exist between the idealized structure assumed for design and the real structure as built in its underground environment can be grouped as follows:

(1) Alignment -- the differences between the actual and the assumed locations of the axes, planes, or other surfaces that define the geometry of the structural member or element.

(2) Proportions -- the differences between the ideal and the actual dimensions of structural elements; for example, variations in the depth of a reinforced concrete section, the amount, spacing, and position of the reinforcement in the slab, and similar other variations.

(3) Structural material properties -- differences between the assumed and the actual physical properties of the structural materials that were used.

(4) Soil resistance properties -- differences between the ideal and the actual physical properties of the soils or other materials that support the structure and within which the structure is placed. This includes not only variations in the basic level of soil resistance assumed, but also variations in the magnitude of this resistance as it may differ from point to point around the structure.

The variations to be expected in the several primary parameters identified above derive from a variety of sources and are subject to varying degrees of control by the structural designer and the builder. Although it may be possible to exercise only little control over the variations that will occur naturally in many structural and soil material properties, it is important that we study the influence of these variations, of whatever magnitude and form they may take, on the behavior and hence on the ultimate resistance of the structure being designed.

Of perhaps even greater importance is the need for a better understanding of the efforts that should be undertaken in the construction process to control the variations that can develop in those parameters over which we can have an effective measure of control. For example, it is possible to exercise higher levels of control and to insist on construction to closer tolerances (though admittedly with an increased cost factor), if it can be demonstrated that such more rigid construction specifications are essential to the attainment of a specified level of protection. Conversely, if it can be shown that somewhat greater construction tolerances are permissible without a significant reduction in the resistance level of the resulting structure, then the economies associated with less restrictive specifications can be achieved. In any event, without information beyond that which we now possess in regard to the significance of variations in these several parameters, it is impossible to prepare a set of construction specifications that are consistent with the physical conditions that prevail and with a specified probability of achieving a stipulated level of protection to a given set of input loading conditions.

All the parameters identified above are significant in the full evaluation of the resistance of a given soil-structure system; but the influence of variations in some of these parameters is more easily dealt with than are variations in others. For many comparatively simple geometric forms and loading conditions, the influence of variations in structural material properties can be easily determined. It may be true that to establish the significance of these variations a large amount of more or less routine computational effort will be required; but simple methods exist for the study of the influence of such parameter variations. Similarly, methods are also readily available whereby for simple geometrical forms the influence of unintended variations in the proportions (widths, thicknesses, reinforcement steel percentages, etc.) on the resistance of the structural element are also easily evaluated; although again, a substantial amount of routine computation effort may be required.

At the present time, however, no procedures exist whereby the effects of departures from the specified structural geometry (variations in radius around an arch, for example) or in the uniformity of soil resistance around the structure can be readily determined. Consequently, in this effort primary attention was given to the study of the influence of variations in these latter two parameters, although the program that was developed is capable also of considering the influence of variations in the former two parameters as well.

2. General Method of Analysis:

To obtain a program of sufficiently general character that it would have wide use in the study of the problem described above, it was necessary to represent the buried structure and the soil which surrounds it as a lumped parameter, soil-structure model, the response of which to superimposed blast loadings could be studied by existing numerical methods of analysis. Consequently, the soil-structure system was represented as a series of concentrated masses which were connected by massless bars; these bars, though massless, retained their axial and bending stiffnesses. Similarly, the applied blast-induced loads, the soil resisting forces, and the internally generated structural resistances were also concentrated at the several mass points.

Although they will be discussed in detail in later sections of this report, it is appropriate to identify here the elements of the mathematical model to which attention must be given. The problem areas encountered in the development of a lumped parameter model that would be equivalent to the real system include the following:

(1) The number and magnitude of the masses used to represent the system.

(2) Evaluation of the internal structure resistances, and the concentration of these resistances at the mass points.

(3) Representation, as a function of displacement, of the resistance offered by the soil to motion of the structure, and the concentration of these soil resisting forces at the mass points.

(4) Representation of the blast-induced free-field forces in the soil surrounding the structure, and the concentration of these blast forces at the mass points of the model.

(5) Establishment of criteria for "failure" of the structure to serve as a basis for comparison of the effects of variations in the several parameters of interest.

After having defined the several elements of the mathematical model identified above, it was then possible to write a computer program, using numerical methods, to solve for the response of the model to a variety of load functions that may be imposed upon it. A detailed description of the computer program that was developed for this purpose is given in Section III of this report.

3. Development of Lumped Mass Model:

The several elements of the mathematical model of the actual soil-structure system were identified in the preceding section. In the paragraphs that follow, more detailed discussion of the proper evaluation of each of these elements is given.

(a) Number of Mass Points: It is impossible to specify in general terms the number of mass points that should be selected to represent a particular real system. The number of mass points that should be used in a given case depends upon the geometrical complexity of the system being represented, the degree of symmetry in the system, and the accuracy to be sought in the solution. Consequently, the computer program was prepared to permit the use of any number of mass points. As far as the program itself is concerned, the number of mass points used is limited only by the size of the available computer system.

(b) Size of Equivalent Masses: For a structural element for which the dynamic response to a given loading is known or can be determined, it is possible to define the size of the masses and the character of the resistance functions that are required to ensure equivalence between the response of the structural element and the response of a lumped parameter model of it. It is, however, impossible to do this for the very complex soil-structure system that is being considered here. There is some uncertainty in regard to the portion of the structure that should be lumped at the mass concentration points; but far greater uncertainty exists in regard to the amount of the surrounding soil that should be assumed to respond with the structure and, hence, that should be included in the concentrated mass of the mathematical model.

Some guidance in this regard is given by Whipple [1,2] from whose work it may be concluded that the period of vibration of a buried arch, as it responds to the forces imposed by the passage of an airblast wave across the ground surface above it, is probably about the same as the period of the same arch when completely above ground. That is to say, the mass of the responding system should be increased because of the surrounding soil that moves with it by approximately the same amount by which the resistance of the arch is augmented by the resistance of the soil adjacent to it. Consequently, assuming the structure to be such that its periods of vibration can be evaluated in an aboveground situation, the equivalent mass and soil resistance that should be employed in the representation of the buried soil-structure system could be determined by trial and error to give approximately the same periods of vibration that would exist in the aboveground case.

Some further insight into this question is given by the studies which show that for a perfect fluid, a volume of fluid included within a distance of one radius of a submerged cylindrical section can be assumed to respond with the circular structure and hence should be considered as effective mass. Soil, however, is obviously not a fluid; hence, the extent to which this criterion for effective mass is applicable is uncertain.

In view of these factors, the computer program for the analysis of the structures to be considered here permits the use of any effective mass; it remains for the user of the program to select the effective mass that he considers most appropriate for the conditions being studied. It should also be noted that for the parameter studies that will be made using this program, the question of the correct effective mass is probably not important in a given case. It will be remembered that the objective of the project was to develop a program to study the influence of variations in parameters; the magnitude of the soil mass can itself be considered as such a parameter and the significance of variations in it can be evaluated in this fashion. If the results of such studies should indicate that the amount of soil that is assumed to respond with the buried structure influences substantially the structure's resistance to blast forces, this is in itself a significant element of information and one that would indicate strongly the need for a research effort directed specifically to this problem.

(c) Representation of Soil Resistance: Because of the nature of this study, no attempt was made to relate the soil resistance function used in the mathematical model to any real soil situation. It was, however, necessary that the basic soil resistances be reasonable and that provisions be made in the computer program not only to study the influence on the structural resistance of variations in the basic resistance, but also to permit the study of the influence of a variable soil resistance around the structure. It will

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[1] Whipple, C. R., "The Dynamic Response of Shallow-Buried Arches Subjected to Blast Loading," Report for Air Force Special Weapons Center, Contract No. AF 29(601)-2591, Project No. 1080, University of Illinois, 1961. (UNCLASSIFIED).

[2] Whipple, C. R., "Numerical Studies of the Dynamic Response of Shallow Buried Arches Subjected to Blast Loading," Draft of Report for Air Force Special Weapons Center, Contract No. AF 29(601)-2591 and AF 29(601)-4508, Project No. 1080, University of Illinois, 1961 (UNCLASSIFIED).

be remembered that one of the parameters to which attention was to be directed initially was the influence of the introduction of "soft spots" at various points around the structure in relation to the level of soil resistance that exists generally around the structure.

It is recognized that in the real case the soil resistance to motion of a structure embedded within it is a highly variable and uncertain function, and that it depends on the soil type, the moisture conditions, the <u>in situ</u> stress conditions, the nature and distribution of the motions of the deforming structure, and many other factors. It was decided, however, that for this initial study the soil resistance would be restricted to the case of a linearly elastic soil which was capable of carrying only compressive stress, and which unloaded to zero stress on the same modulus of deformation upon which it was loaded.

Although this form of resistance function is obviously not a true representation of any actual soil, it is considered to be a reasonable approximation of the behavior of many soil types, at least under conditions of relatively small deformation. Before more extensive studies are made into the significance of a wide variety of soil resistance forms, it seems appropriate that a more nearly complete understanding be acquired of the effects of variations in soil resistances of this relatively simple and basic form. The computer program has, therefore, been written for this type of soil resistance function; but it could be modified without great effort to permit the study of more complex load forms. A further discussion of the soil resistance functions and the way in which the soil resistance was concentrated at the several mass points is given in the detailed discussion of the development of the computer program in Section III.

(d) <u>Representation of Load Function</u>: From the standpoint of representing the actual soil-structure system by an equivalent lumped-mass mathematical model, the proper representation of the blast-induced load function is the most difficult problem and is probably the source of greatest uncertainty. In the actual physical case, it is clearly impossible to separate the soil resistance function and the applied load funtion on the structure for the obvious reason that these two factors combine in some fashion to produce the pressure that exists on the soil-structure interface. This question is, of course, the very heart of the soil-structure interaction problem which is receiving much research emphasis, but which, as stated at the outset, is beyond the scope of this present study.

It is clearly incorrect in the real case to assume that the pressures transmitted to the buried structure from the blast-induced free-field stresses in the soil surrounding the structure are independent of and are unaffected by the deformation of the structure. An effort was made in the early stages of this investigation to recognize the interdependence of soil resistance and load application to the structure by endeavoring to introduce the load functions as displacements of the bases of the springs that were used in the model to represent the soil resistance. Because of the relationships that are known to exist between free-field soil stress and particle velocity in the soil, this approach to the soil-structure interaction problem is still thought to be potentially valid. However, attempts to arrive at a satisfactory model using this approach have not as yet been successful; the primary source of difficulty is an inability to represent properly the load function as it is influenced by the relative deformations of the soil spring base and of the structure at its point of attachment to the spring. It is a relatively simple matter to translate a free-field soil stress pulse into corresponding free-field solid particle motions and hence into resulting forces in a soil spring. To account at the same time for the effect on the spring force of the motion of the structure, which is a combination of the motion of the structure relative to the soil immediately around it as well as of a rigid body motion of the structure as it moves in some manner with the soil surrounding it, is much more difficult.

Therefore, acknowledging the incorrectness of it, but recognizing at the same time that there presently exists no better alternative, we assumed the blast-induced load functions used for this study to be directly related to and derivable from the free-field blast-induced stresses that exist in the soil surrounding the structure. It is appropriate to note here that the computer program was written so that a variety of multilinear free-field soil pressure functions could be studied; the details of these pressure function representations, and the techniques that were employed to accumulate the free-field pressures and concentrate them as forces applied directly to the mass points of the mathematical model are contained in Section III.

One further restriction in regard to the load pulse should also be noted. No provision has been made for varying the shape of the load pulse as it propagates across the structure; the same basic free-field stress pulse is assumed to exist at all points in the soil which surrounds the structure. However, the program is written so that the pressure pulse may approach the structure and traverse it in any direction that may be appropriate.

(e) <u>Structural Resistance</u>: As noted earlier, the structure is represented, for purposes of analysis, as a series of concentrated masses connected by massless bars or links which, though massless, develop internal resisting forces as deformations are imposed upon them. Thus, it was necessary to develop a method whereby these internal resisting forces, which act as reactions on the concentrated mass points, may be computed from the deformations that are imposed upon the bars.

In the process of the dynamic analysis of the entire lumped-mass system, the changes in the coordinates of the mass points, and hence of the ends of each connecting bar, will be determined. From these changes in the mass point coordinates, the changes in connecting bar lengths and the rotations of one bar relative to the adjacent bars can be readily computed. From the total change in bar length, which is assumed to be uniformly distributed throughout the length of the bar, and from the total rotation of adjacent bars, which is assumed to be the accumulation of uniform curvature over a length equal to the length of one bar, the strain distributions that will exist on the structural cross sections at each end of a bar, and hence on each side of a mass point, are readily determined. Similarly then, from these strain distributions, the resulting thrusts, moments, and corresponding shears are computed. The shears and thrusts thus determined are the internal resisting forces that act on the concentrated mass points.

In concept, the procedure outlined above is relatively simple and straightforward; in reality, the development of a computer program to perform this phase of the analysis is quite complex. The program must be sufficiently general to evaluate these forces for a reinforced concrete section as it responds to the combined effects of axial stress and bending well beyond the region of elastic behavior of these materials. The details of the program that was developed to compute these internal resisting structural forces are presented in Section III.

(f) <u>Failure Criteria</u>: Since the objective of this study was to determine the influences on the failure load of a buried structure of variations in significant parameters such as soil resistance, structural geometry, and material properties, it is necessary to define a structural failure condition to serve as a basis against which these comparative parameter effects can be measured.

In an actual case, structural failure would generally be defined in terms of structural deformations or motions that are of sufficient magnitude to impair to a specified degree the ability of the structure to function as it was originally intended. Since this study is not related to a particular structural type or to structures designed to perform a particular function, it is impossible to define structural failure on the bases outlined above. By making comparatively minor changes in the computer program, it would be possible to specify a variety of failure criteria as they may be appropriate for various structural types and conditions. However, in the program as currently written, failure was somewhat arbitrarily defined to exist when the deformations in the structure had developed in sufficient magnitude at enough points in the structure to transform the structure into a mechanism. Thus, for a two-hinged arch to which the program has thus far been applied, failure was assumed to have occurred when general yielding developed across the structural cross section at two points on the circumference of the arch.

Although a mechanism might not necessarily be developed, it was also assumed that failure would have occurred when the concrete strains at any two points in the arch exceeded the concrete strain at which the concrete would have crushed and, hence, would have suffered a reduction in stress with further increase in strain. It was further assumed that a combination of the general yielding case and the concrete crushing case at any two points in the arch would also constitute failure. Although such a failure criterion may well be inappropriate for a given physical situation, it is considered to be reasonable as a basis upon which to make the comparative parameter variation effect studies for which this computer program was written.

SECTION III

DEVELOPMENT OF COMPUTER PROGRAM

1. General Description of Program:

The program was developed for use on the University of Illinois IBM 7094 computer. It was written in FORTRAN, but it was compiled and run on FASTRAN, a compiler developed by the Department of Computer Science at the University. FASTRAN is faster and more efficient than FORTRAN; however, in almost all other aspects it is the same as IBM's FORTRAN.

The program itself consists of a main program which merely handles data, stops the computer at the proper time, and calls several subroutines as they are needed. A total of eight subroutines was used, although not all of them are called from the main program; some are called from other subroutines. The eight subroutines, BETA, CHECK, DEFORM, EXCITE, EXTERN, INIT, LOCATE, and YIELD, each of which will be discussed in detail later, perform all computations required in the analysis.

During the development of the program, each of the subroutines was written and checked for errors before proceeding to the next. As a result most of the variables used are in DIMENSION and/or COMMON STATEMENTS.

A logic flow diagram of the analysis used is shown in Figure 1. This method of analysis is typical of familar numerical integration techniques of solving vibration problems; hence, detailed discussion of it here is unnecessary. However, further comment in regard to the more complex aspects of it, as applied to the type of problem being considered in this study, is given in the descriptions of the several subroutines that follow in later sections.

As discussed earlier, the soil-structure system is approximated as a lumped-mass model consisting of masses, bars, and soil springs. Such a model is illustrated in Figure 2.

The main program reads all input data and writes it out in the form of an echo print to facilitate checking the data. These input data and the form in which they are entered into the computer are presented in the appendix. These data include the initial geometry of the model, including the soil mass that is assumed to respond with the model; a description of the stress-strain curves for concrete and for steel; a description of the blast pressure pulse, including its orientation with respect to the horizontal, and the ratio between horizontal and vertical free-field blast pressure; the seismic velocity of the soil, and the soil resistance function; the number of fibers used to represent the cross section of the structure, the area of reinforcing steel, and the location of this steel in the cross section; the initial time for the program; and several constants that define acceptable limits of computational accuracy and control the print-out from the program.

The geometry of the model is read into the computer by specifying the total number of joints, or mass points, in the structure (limited in the program as written to eleven, but readily changeable to any desired number),

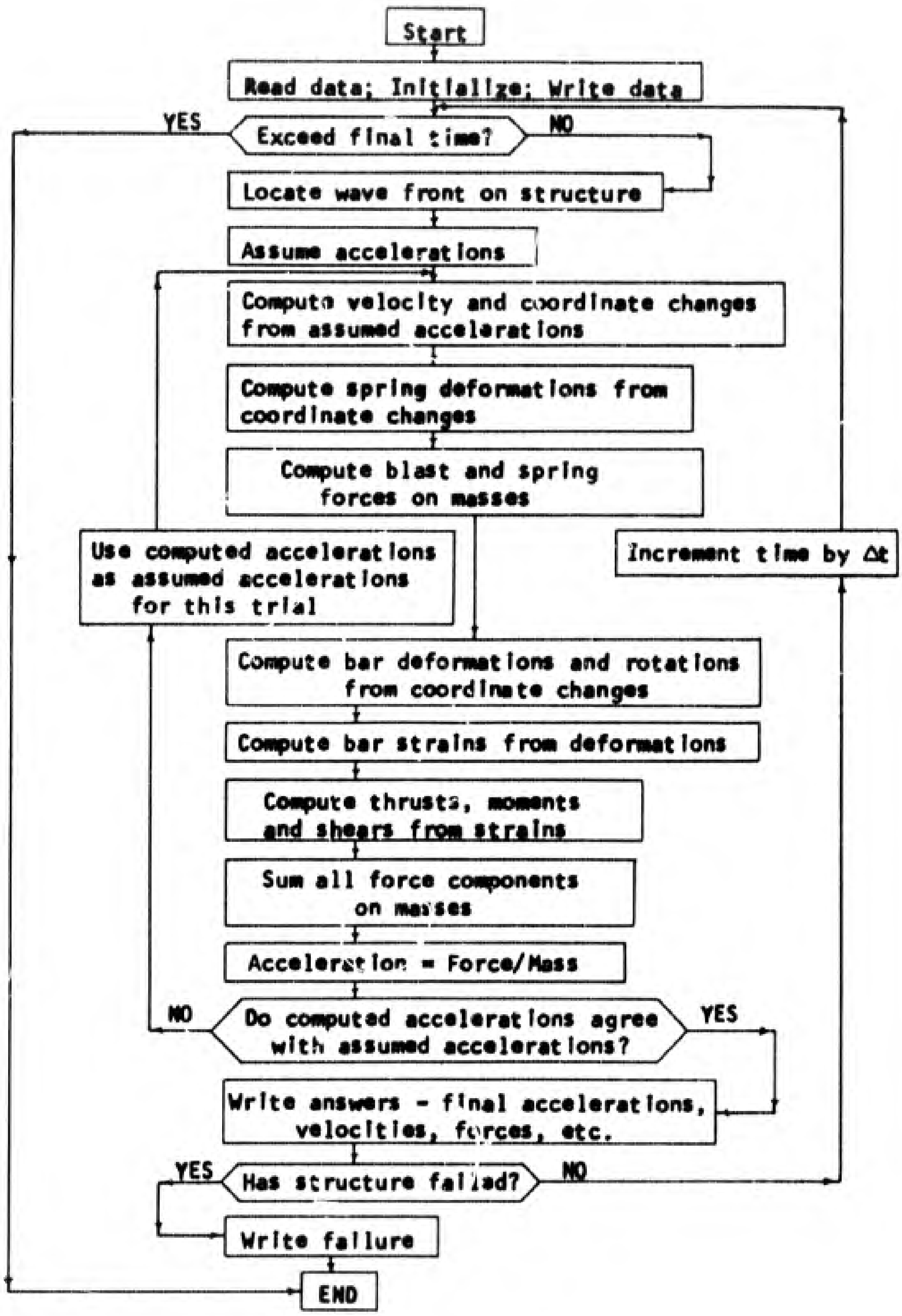

FIGURE 1. LOGIC FLOW DIAGRAM

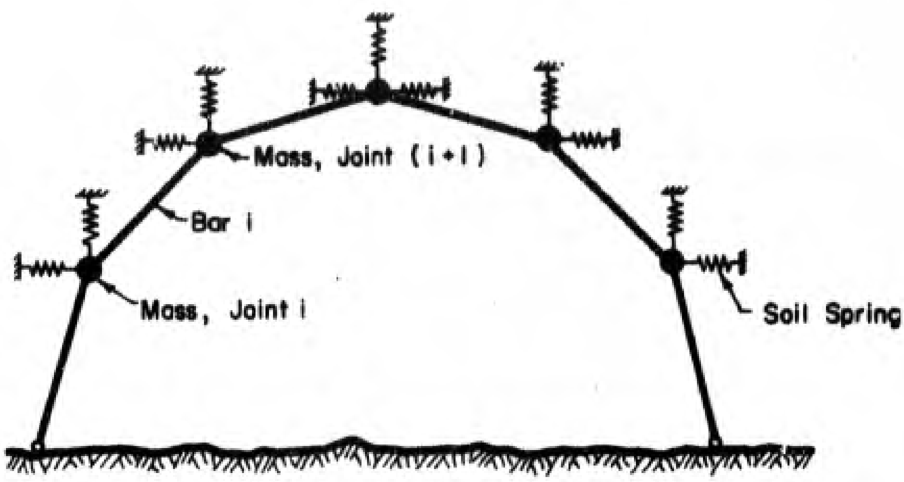

FIGURE 2. LUMPED MASS MODEL OF STRUCTURE

the length of the bars connecting the mass points (Initially, all bars have the same length.), and the angle that each bar makes with the horizontal. The program sets the x and y coordinates of Joint 1 equal to zero, and then, in the main program, computes the coordinates of the other joints from the following equations,

$$x_{(i+1)} = x_i + L \cos\alpha_i$$

$$y_{(i+1)} = y_i + L \sin\alpha_i$$

in which L is the original length of the bars in the model and α_i is the acute angle that bar i makes initially with the horizontal.

After the input data have been read in and the mass point coordinates have been computed as described above, the subroutine INIT is called to initialize the several variables at their proper values and the subroutine LOCATE is called to place the pressure pulse on the structure and begin the actual analysis.

Full comprehension of the complete program, including the interaction of the several subroutines, can be obtained only from a detailed study of the program which is presented in its entirety in the appendix, together with the discussions of the several subroutines that are contained in the sections that follow herein. However, it is informative to note here the purposes of each of the several subroutines. These purposes, briefly stated and without discussion and explanation are as follows:

INIT	- Initializes the variables to their proper initial values.
LOCATE	- Locates the blast pressure pulse in relation to the masses of the model.
BETA	- Performs the numerical integration of the equations of motion to yield changes in the mass point coordinates during the time interval, Δt, resulting from the application of the blast forces.
DEFORM	- Computes the internal resistances of the structure that are consistent with the mass point displacements that are computed in BETA.
EXTERN	- An adjunct to DEFORM to assure compatability of the axial forces and moments computed in DEFORM.
EXCITE	- Computes the soil spring forces that are generated by the mass point displacements determined in BETA.
YIELD	- Maintains the time histories of the strains in the concrete and steel in each of the several elements of the model.
CHECK	- Determines, on the basis of criteria input to it, whether failure has occured.

As noted earlier, a complete printout of the entire program, including the eight subroutines, is presented in the appendix. A list of the FORTRAN variables used in the program, along with their definitions, is also given.

For simplicity of presentation and discussion, the variables used in the following discussions of the several subroutines are frequently different from their FORTRAN counterparts. Therefore, the variables are defined when first used in program development and are summarized for convenience in alphabetical order in the front of this report.

2. Subroutine BETA:

The subroutine BETA performs the numerical integration required by the equations of motion in the dynamic portion of the analysis. The method used is the "Beta Method" developed by Newmark[3] at the University of Illinois.

Initial conditions of displacement, velocity, and acceleration are assumed to be known at time t. The acceleration of the mass at time (t+Δt) is then assumed, and the corresponding velocity and displacement of the mass at time (t+Δt) are computed. The soil and structural resisting forces that correspond to this computed displacement are then determined, which when used together with the applied force at t+Δt make it possible to compute an acceleration at that time. If this computed acceleration at t+Δt is in agreement with the assumed acceleration, the assumed acceleration is correct and the resulting structural configuration is the actual configuration at time t+Δt; if not, the computation cycle must be repeated until agreement is obtained. The displacement, velocity, and acceleration thus determined at t+Δt are then taken as a new set of initial conditions and the procedure is used to determine the conditions at the end of the next time interval.

The equations used in the Beta Method are:

$$\dot{x}_i^{(t+\Delta t)} = \dot{x}_i^t + \frac{1}{2} (\Delta t)\ddot{x}_i^t + \frac{1}{2} (\Delta t)\ddot{x}_i^{(t+\Delta t)} \quad (1)$$

$$\dot{y}_i^{(t+\Delta t)} = \dot{y}_i^t + \frac{1}{2} (\Delta t)\ddot{y}_i^t + \frac{1}{2} (\Delta t)\ddot{y}_i^{(t+\Delta t)} \quad (2)$$

$$\Delta x_i^{(t+\Delta t)} = (\Delta t)\dot{x}_i^t + (\frac{1}{2} - \beta)(\Delta t)^2 \ddot{x}_i^t + \beta(\Delta t)^2 \ddot{x}_i^{(t+\Delta t)} \quad (3)$$

$$\Delta y_i^{(t+\Delta t)} = (\Delta t)\dot{y}_i^t + (\frac{1}{2} - \beta)(\Delta t)^2 \ddot{y}_i^t + \beta(\Delta t)^2 \ddot{y}_i^{(t+\Delta t)} \quad (4)$$

in which

$\Delta x_i^{(t+\Delta t)}$ and $\Delta y_i^{(t+\Delta t)}$ are displacements of mass i in the x and y directions during the time interval Δt.

[3]Newmark, N. M., "A Method of Computation for Structural Dynamics," Transactions American Society of Civil Engineers, Vol. 127, 1962.

$\dot{x}_i^{(t)}$ and $\dot{y}_i^{(t)}$ are velocities of mass i in the x and y directions at the beginning of the time interval, and are known either as initial conditions or from analysis of the preceding time interval.

$\ddot{x}_i^{(t)}$ and $\ddot{y}_i^{(t)}$ are accelerations of mass i in the x and y directions at the beginning of the time interval, and are known either as initial conditions, or from computations of the preceding time interval.

β is the dimensionless constant used in numerical integration.

The value of the dimensionless parameter β depends on the manner in which the acceleration is assumed to vary between time t and $t+\Delta t$. In the problems solved in connection with this report $\beta = 1/6$ was used. This corresponds to a linear variation of acceleration within the time interval. The time increment Δt must be chosen carefully in order to insure stability and convergence of the numerical process.

In the process of solving the equations of motions listed above it is clearly necessary that the blast forces, soil spring forces, and internal structural resistances be known in order to compute the several accelerations that are needed. These forces are computed in subroutines DEFORM and EXCITE which are discussed in detail later.

In programming the Beta Method for this problem a variable time interval Δt was used. The number of cycles required for convergence is used as the criterion for the choice of Δt. If the problem does not converge in eight cycles, the time interval is reduced to half its value and cycle is restarted at time t=t; on the other hand, if convergence is reached in less than four cycles, the time interval is doubled for the next time increment. In this manner, both convergence and stability of the method are assured.

Convergence in both the x and y directions at <u>all</u> mass points in the model is necessary for the determination of the structural configuration at time $t+\Delta t$. Absolute convergence is, of course, not required; it is necessary only that the acceleration computed to exist at time $t+\Delta t$ be sufficiently close to that which was assumed to maintain acceptable precision in the analysis.

Therefore, convergence can be checked by considering the difference between the assumed and calculated accelerations at t+Δt, without regard to sign, as follows:

$$\Delta \ddot{z}_i = | \ddot{z}_{i\ Assumed} - \ddot{z}_{i\ Calculated} | \qquad (5)$$

where $\ddot{z}_i$ is either $\ddot{x}_i$ or $\ddot{y}_i$.

If $\Delta\ddot{z}_i$ is less than a prescribed percentage of $\ddot{z}_{i\ Calculated}$ then the acceleration of mass i in the direction of interest is considered to have converged. This check is applied to all masses in both the x and the y directions. If, however, $\Delta\ddot{z}_i$ is greater than the permissible difference expressed as a percentage of $\ddot{z}_i$, it is still possible, if $\ddot{z}_i$ is very small, that satisfactory convegence may have been reached. This condition is easily checked by specifying an upper acceptable limit for the absolute value of $\Delta\ddot{z}_i$. If $\Delta\ddot{z}_i$ for all masses is smaller than either of these allowable maximum differences, convergence is assumed to have occurred, and the analysis progresses to the next time interval. On the other hand, if any of the accelerations in the x or y directions of any of the masses fail both the relative and absolute checks, new accelerations are assumed in the x and y directions at each of the masses and the analysis is repeated.

Clearly, the values of $\Delta\ddot{z}_i$ that are considered acceptable depend upon the accuracy sought. Although easily changed, the program as currently written, specifies that $\Delta\ddot{z}_i$ shall be equal to or less than 0.1 in/sec/sec, or 0.05 percent of $\ddot{z}_i$, whichever is larger.

3. Subroutine CHECK:

CHECK is a subroutine which is used to determine whether the structure has failed. It does this by checking the strain intensities in the concrete fibers that are used to approximate the cross section of the structural element, and it is called after acceleration convergence has been obtained on all masses in each time interval.

Conceptually, structural collapse is assumed to have occurred when any one of the following conditions exist.

1) A sufficient number of yield hinges form in the structure to transform it into a mechanism

2) Crushing of concrete occurs in any fiber at the number of locations defined in (1) above.

3) A combination of yield hinges and concrete fiber crushing exists at the number of locations defined in (1) above.

When the criteria indicate that the structure has failed, the computer prints where and how it failed and calls an error routine from the systems library to shut off the computer. As presently written, the program assumes a two-hinged structure; hence, the number of yield hinge or crushing locations defining failure is two.

4. Subroutine DEFORM:

DEFORM is a subroutine which computes axial bar forces, and moments and shears at the joints from changes in the mass point coordinates and the stress-strain curves for concrete and steel. The subroutine uses coordinate changes to compute strains, which are then converted to stresses and finally to forces, moments and shears. It is patterned closely after a similar program developed by Dawkins.[4]

Figure 3 shows bar i connecting joints i and (i+1) at two instants of time. During the time interval Δt the joints have moved to new positions causing coordinate changes of $\Delta x_i^{t+\Delta t}$, $\Delta x_{i+1}^{t+\Delta t}$, $\Delta y_i^{t+\Delta t}$, and $\Delta y_{i+1}^{t+\Delta t}$. The coordinates of joints i and (i+1) at time $t+\Delta t$ are, therefore:

$$x_i^{t+\Delta t} = x_i^t + \Delta x_i^{t+\Delta t}; \quad y_i^{t+\Delta t} = y_i^t + \Delta y_i^{t+\Delta t}$$

$$x_{i+1}^{t+\Delta t} = x_{i+1}^t + \Delta x_{i+1}^{t+\Delta t}; \quad y_{i+1}^{t+\Delta t} = y_{i+1}^t + \Delta y_{i+1}^{t+\Delta t} \qquad (6)$$

Using these new coordinates the slope of bar i at time $t+\Delta t$, $\alpha_i^{t+\Delta t}$ is defined by

$$\alpha_i^{t+\Delta t} = \text{ARCTAN}\left(\frac{y_{i+1}^{t+\Delta t} - y_i^{t+\Delta t}}{x_{i+1}^{t+\Delta t} - x_i^{t+\Delta t}}\right) \qquad (7)$$

Then, the incremental change in α_i, $\Delta\alpha_i^{t+\Delta t}$, during the interval Δt, is computed by

$$\Delta\alpha_i^{t+\Delta t} = \left[\left(\Delta x_{i+1}^{t+\Delta t} - \Delta x_i^{t+\Delta t}\right) \text{SIN}\ \alpha_i^{t+\Delta t} - \left(\Delta y_{i+1}^{t+\Delta t} - \Delta y_i^{t+\Delta t}\right) \text{COS}\ \alpha_i^{t+\Delta t}\right] / \left(L_i^t + \Delta L_i^{t+\Delta t}\right) \qquad (8)$$

The incremental change in the length of bar i, $\Delta L_i^{t+\Delta t}$, during the interval Δt, is computed from

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[4] Dawkins, W. P., "Dynamic Response of a Tunnel Liner-Packing System", Ph.D. Thesis, University of Illinois, 1966.

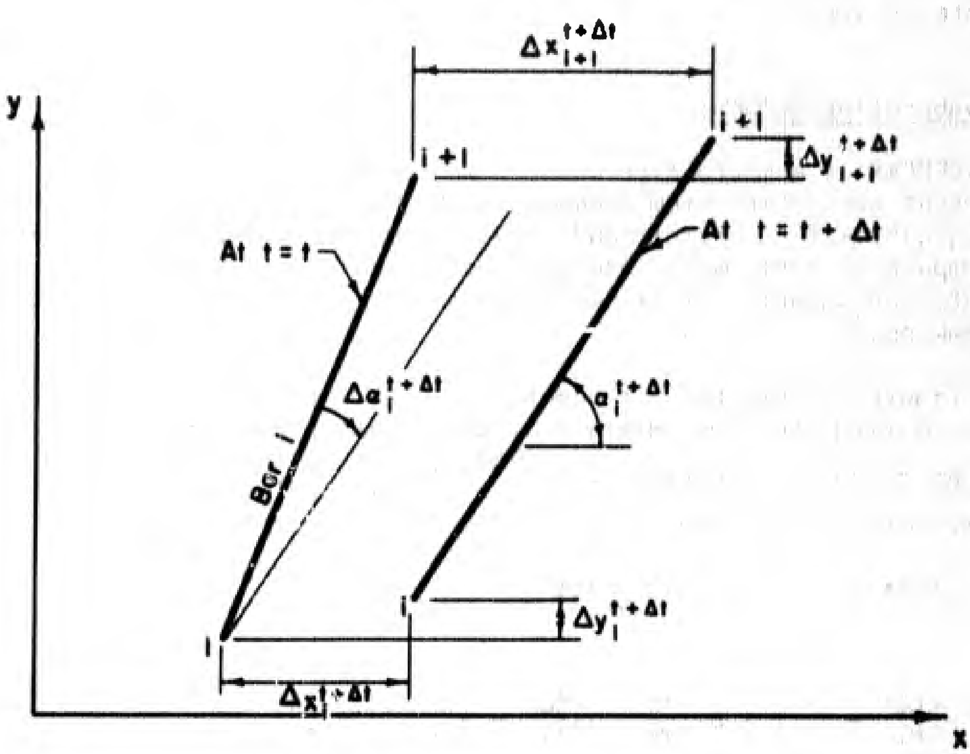


FIGURE 3. DISPLACEMENT OF BAR DURING TIME INCREMENT

$$\Delta L_i^{t+\Delta t} = \left(\Delta x_{i+1}^{t+\Delta t} - \Delta x_i^{t+\Delta t}\right) \cos \alpha_i^{t+\Delta t}$$

$$+ \left(\Delta y_{i+1}^{t+\Delta t} - \Delta y_i^{t+\Delta t}\right) \sin \alpha_i^{t+\Delta t} \tag{9}$$

It is important to note that the equations above give values for <u>changes</u> which occur during the time interval between t and t+Δt. To obtain the total change in bar length, ΔL_i^{TOTAL} it is necessary only to sum the previously computed incremental values of ΔL_i as follows:

$$\Delta L_i^{TOTAL} = \sum_{t=0}^{t=t+\Delta t} \Delta L_i \tag{10}$$

Similarly, the total rotation of bar i, $\Delta\alpha_i^{TOTAL}$, is obtained as the sum of the incremental rotations.

$$\Delta\alpha_i^{TOTAL} = \sum_{t=0}^{t=t+\Delta t} \Delta\alpha_i \qquad (11)$$

From these values of total bar rotation and change in length, strains and curvatures can be computed. The average strain in bar i is

$$\epsilon_{BARi}^{AVG} = \Delta L_i^{TOTAL}/L \qquad (12)$$

where L is the original bar length and carries no subscript since all the bars originally have the same length.

It is assumed initially that all rotations are concentrated at the joints; that is, the bars rotate as rigid bodies. Figure 4 shows joint i with portions of bars i-1 and i attached. Bar i has undergone a positive angle change (clockwise rotation) $\Delta\alpha_i^{TOTAL}$ while bar i-1 shows a negative angle change (counter-clockwise) $\Delta\alpha_{i-1}^{TOTAL}$. The rotations of these two bars results in a decrease ρ_i^t, the angle between the two bars. This angle change, $\Delta\rho_i^t$, can be computed from

$$\Delta\rho_i^t = \Delta\alpha_i^{TOTAL} - \Delta\alpha_{i-1}^{TOTAL} \qquad (13)$$

Equation (13) gives a positive value to $\Delta\rho_i^t$ when the intersection angle is reduced. An average value of curvature at the joint, ϕ_{JTi}^t, is obtained by assuming the total angle change, $\Delta\rho_i^t$, to be uniformly distributed over a distance equal to one bar length.

$$\phi_{JTi}^t = \Delta\rho_i^t/L \qquad (14)$$

Equations (13) and (14) are consistent with a sign convention for which a decrease in the central angle ρ_i produces a positive curvature at the joints. By defining a positive moment as one which produces compressive strains on the outside of the structure, moments in the model are consistent with those given by the differential equation for bending,

$$M = - EI \frac{d^2y}{dx^2} \qquad (15)$$

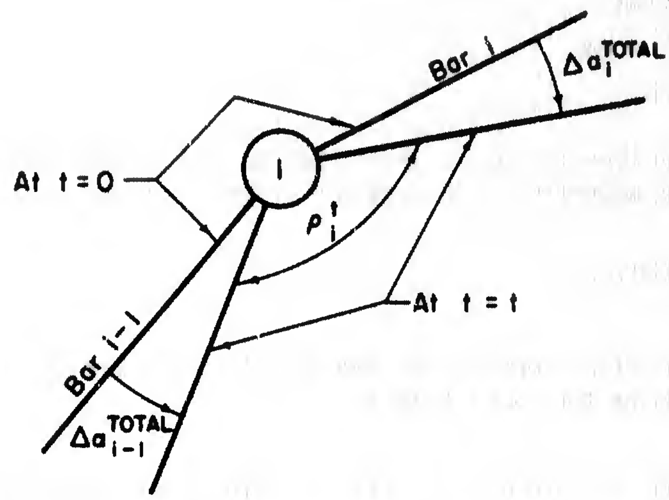


FIGURE 4. RELATIVE BAR ROTATIONS AT MASS

where M is the bending moment, E the modulus of elasticity of the material comprising the section, I the moment of inertia, and $\frac{d^2y}{dx^2}$ the curvature of the section.

The preceding equations yield average axial strains in the bars and average curvatures at the joints of the model. However, because of the nature of the model and the fact that inelastic response of the system is to be considered, it was necessary to develop a procedure to account for the interaction of axial force and moment both at the joints and in the bars. Thus, the axial force in bar i was determined from the average axial strain computed from Equation (12) for the bar together with bending strains which were assumed to be the average of the bending strains defined by the curvatures at joints i and i+1 as given by Equation (14). Similarly, the moment at joint i was computed from the strains given by the curvature at that joint, Equations (14), together with an axial strain which was assumed to be the average of the axial strains of the two adjacent bars as given by Equation (12). The following equations are consistent with these assumptions.

The average axial strain in joint i, ϵ_{JTi}^{AVG}, is taken as

$$\epsilon_{JTi}^{AVG} = \frac{\epsilon_{BARi}^{AVG} + \epsilon_{BAR\ i-1}^{AVG}}{2} \tag{16}$$

and the curvature at mid-length of bar i, ψ_{BARi}, is assumed to be

$$\psi_{BARi} = \frac{\psi_{JTi} + \psi_{JT\ i+1}}{2} \tag{17}$$

Assuming the angle changes to be sufficiently small that the sine of the angle is approximately equal to the angle expressed in radians, and adopting a sign convention that is positive when z, a distance, is above the plastic centroid the effects of axial and bending strains can be combined using the following expressions:

$$\epsilon_{BARi}^{z} = \epsilon_{BARi}^{AVG} \pm z\ \psi_{BARi} \tag{18}$$

$$\epsilon_{JTi}^{z} = \epsilon_{JTi}^{AVG} \pm z\ \psi_{JTi} \tag{19}$$

where ϵ_{BARi}^{z} and ϵ_{JTi}^{z} are strains in bar i and joint i at some distance z above or below the plastic centroid. Figure 5 shows this strain summation for bar i. For numerical computation, the bars and joints, whose cross section is shown in Figure 6, are represented by a number of fibers as shown in Figure 7. The resulting equations for the strains in fiber j of joint i and bar i are

$$\epsilon_{BARi}^{j} = \epsilon_{BARi}^{AVG} - \left[\frac{H}{2} - \left(\frac{2j-1}{2}\right)\frac{H}{n_f}\right] \psi_{BARi} \tag{20}$$

$$\epsilon_{JTi}^{j} = \epsilon_{JTi}^{AVG} - \left[\frac{H}{2} - \left(\frac{2j-1}{2}\right)\frac{H}{n_f}\right] \psi_{JYi} \tag{21}$$

in which ϵ_{BARi}^{j}, and ϵ_{JTi}^{j} are the strains in fiber j of bar i and joint i, H is the total depth of the cross section and n_f is the number of fibers used to approximate the cross section.

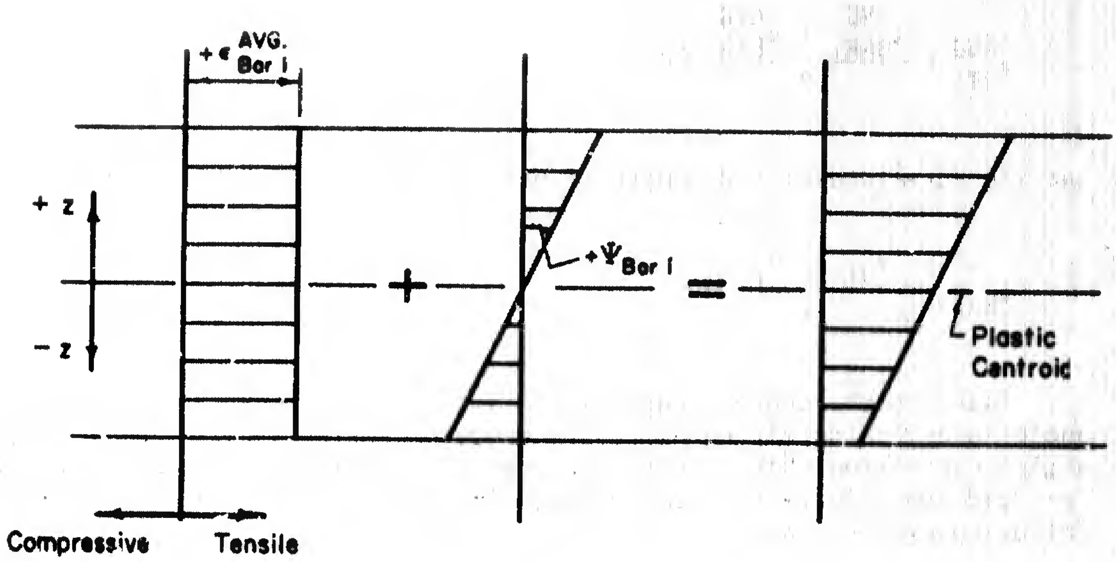


FIGURE 5. STRAIN SUMMATION IN BAR

The stress distribution can now be obtained from applicable stress-strain curves. Figure 8 is an idealized trilinear stress-strain curve of concrete, on which the following notation is used.

E_c = modulus of elasticity

ϵ_{cr} = strain at which concrete begins to fail

ϵ_u = ultimate strain or strain at which the concrete crushes

ϵ_o = strain axis intercept

The capitalized names in parentheses are the FORTRAN names assigned to the variables. The concrete is assumed to unload along a line parallel to E_c, its initial modulus of elasticity. The tensile strength of concrete is neglected.

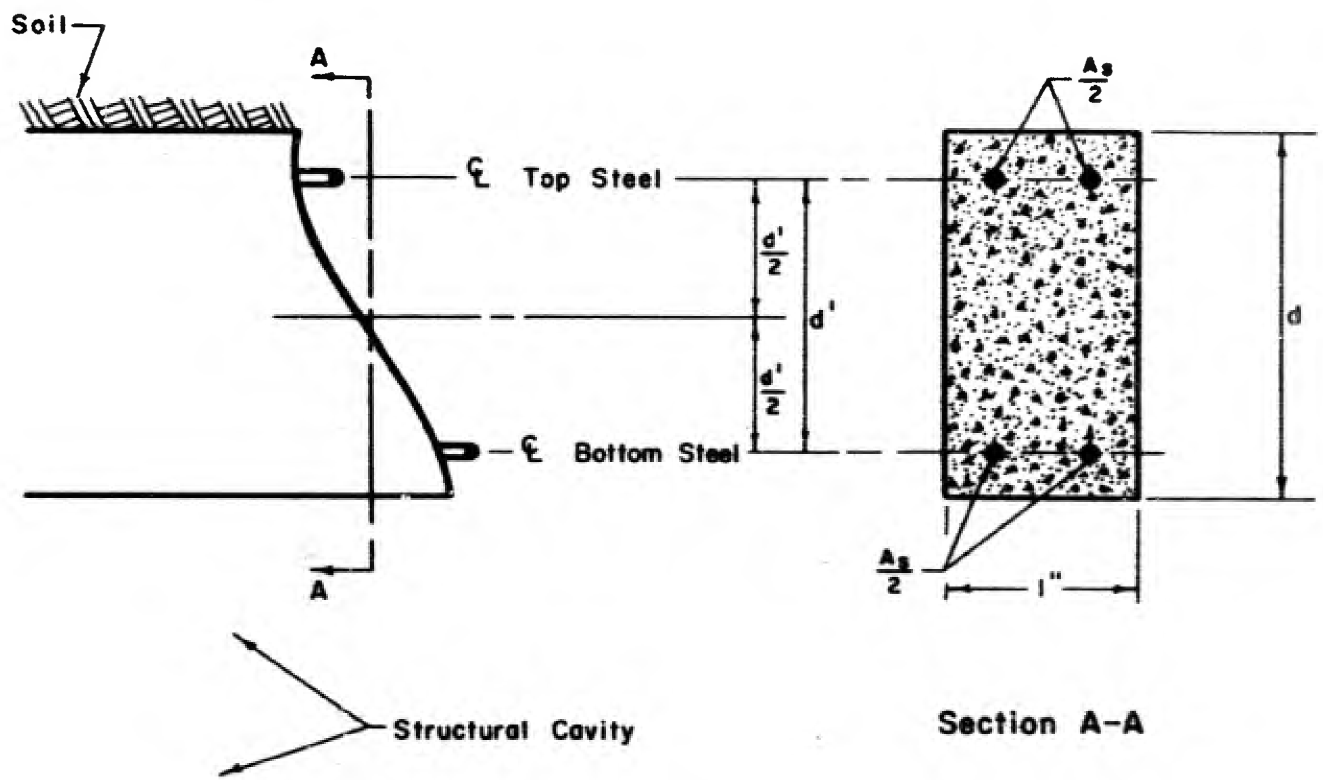


FIGURE 6. TYPICAL STRUCTURAL CROSS SECTION

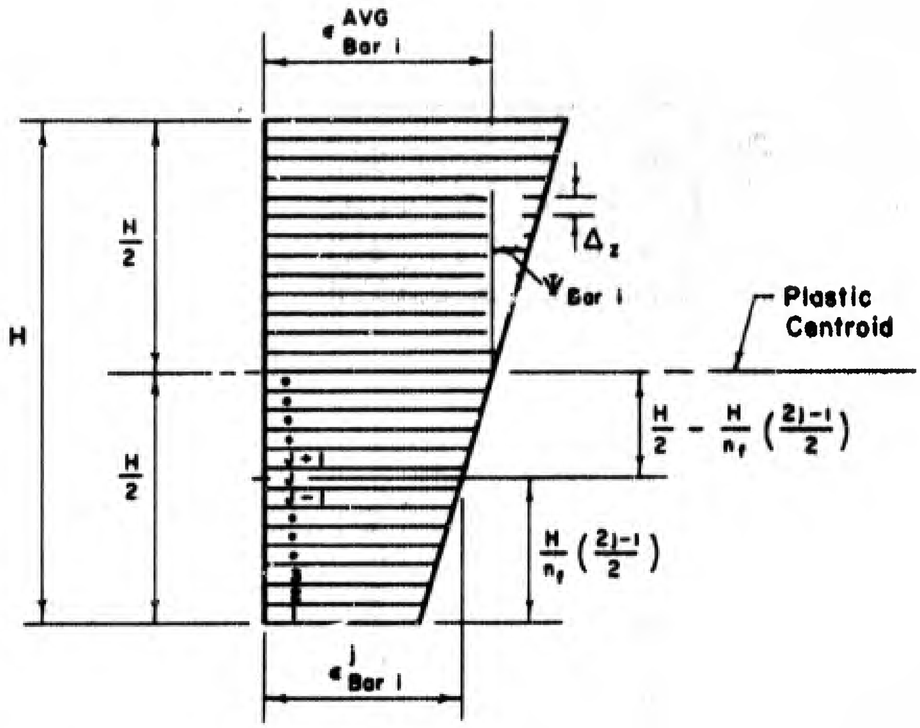


FIGURE 7. FIBER STRAIN REPRESENTATION FOR COMPUTER ANALYSIS

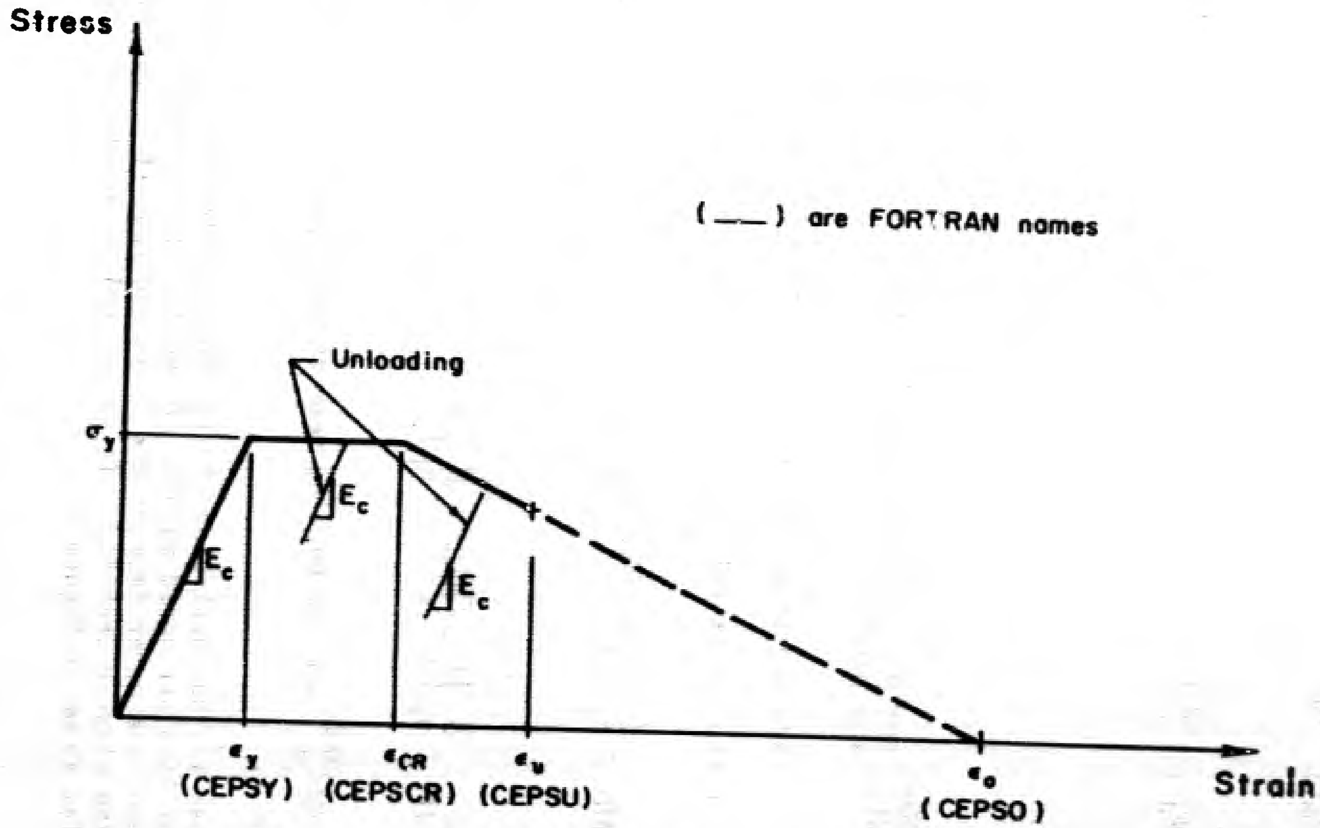


FIGURE 8. IDEALIZED CONCRETE STRESS–STRAIN DIAGRAM

The axial forces in the bars and joints are then computed from the stresses using the following equations:

$$FORCE_{BARi}^{CONC} = \sum_{j=1}^{n_f} (\sigma_{BAR}^{j} \cdot \frac{H}{n_f}) \tag{22}$$

$$FORCE_{JTi}^{CONC} = \sum_{j=1}^{n_f} (\sigma_{JTi}^{j} \cdot \frac{H}{n_f}) \tag{23}$$

where

$FORCE_{BARi}^{CONC}$, $FORCE_{JTi}^{CONC}$ are the forces developed in the concrete of bar and joint i

σ_{BARi}^{j}, σ_{JTi}^{j} are the stresses in fiber j of bar i and joint i.

Similarly the moments in the joints and bars are computed from

$$MOM_{BARi}^{CONC} = \sum_{j=1}^{n_f} \left\{ \left(\sigma_{BARi}^{j} \cdot \frac{H}{n_f}\right) \left[\frac{H}{2} - \left(\frac{2j-1}{2}\right) \frac{H}{n_f} \right] \right\} \tag{24}$$

$$MOM_{JTi}^{CONC} = \sum_{j=1}^{n_f} \left\{ \left(\sigma_{JTi}^{j} \cdot \frac{H}{n_f}\right) \left[\frac{H}{2} - \left(\frac{2j-1}{2}\right) \frac{H}{n_f} \right] \right\} \tag{25}$$

in which MOM_{BARi}^{CONC} and MOM_{JTi}^{CONC} are the bending moments developed by the concrete bar in bar i and joint i.

The preceding analysis has neglected the reinforcing steel in the bars and joints. The steel is distributed equally in two layers, one near the inner and the other near the outer face of the cross section; it is placed symmetrically about the plastic centroid. It is assumed to behave as a purely elasto-plastic material shown in Figure 9.

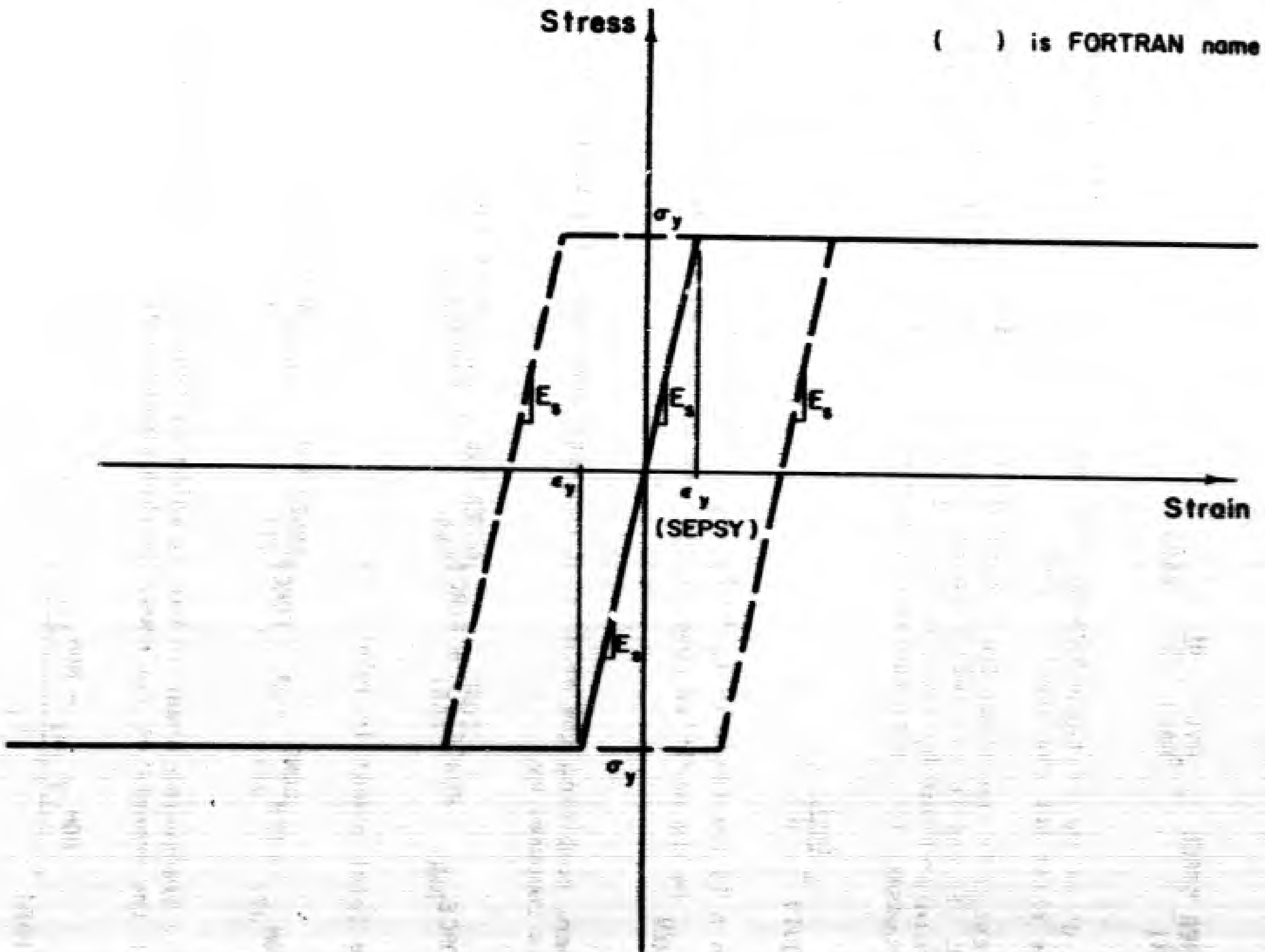


FIGURE 9. IDEALIZED STEEL STRESS–STRAIN DIAGRAM

On the basis of the preceding analysis of concrete strains, the strains in the reinforcing steel of bar i are

$$\epsilon_{BAR\,i}^{OUTER\ STEEL} = \epsilon_{BAR\,i}^{AVG} + \frac{d'}{2}\ \phi_{BAR\,i} \tag{26}$$

and

$$\epsilon_{BAR\,i}^{INNER\ STEEL} = \epsilon_{BAR\,i}^{AVG} - \frac{d'}{2}\ \phi_{BAR\,i} \tag{27}$$

in which d' is the distance between the layers of reinforcement. Similar equations exist for the steel in joint i.

Stresses in the steel are determined from the stress-strain diagram of Figure 9. Forces in the reinforcement are computed by multiplying the area of the reinforcement by the stresses. If any of the steel is in compression, it is necessary to use an equivalent area which is given by

$$A_{EQUIV} = \frac{(n-1)}{n}\ A_s \tag{28}$$

in which n is the ratio of E_s to E_c, A_s is the area of the reinforcing steel and A_{EQUIV} is the modified compression area of the reinforcement.

Then, combining the effects of concrete and steel, the total force in bar i is computed by

$$FORCE_{BAR\,i} = FORCE_{BAR\,i}^{CONC} + FORCE_{BAR\,i}^{OUTER\ STL} + FORCE_{BAR\,i}^{INNER\ STL} \tag{29}$$

and the total moment in joint i is

$$MOM_{JT\,i} = MOM_{JT\,i}^{CONC} + d' \left(FORCE_{JT\,i}^{INNER\ STL} - FORCE_{JT\,i}^{OUTER\ STL} \right) \tag{30}$$

The transverse shear in bar i, which corresponds to the difference between the moments at its ends, is then computed as

$$V_{BAR\,i} = \frac{MOM_{JT\ i+1} - MOM_{JT\,i}}{L_i} \tag{31}$$

Figure 10 shows bar i with positive thrusts, shears and moments acting upon it. These are the values obtained from equations (29), (30), and (31).

It is of interest to note that the method presented above cannot always be relied upon to locate the neutral axis of the cross section properly. As an example, consider a reinforced concrete beam subjected to pure bending. Using the above analysis, a moment and a compressive thrust would be computed. This thrust, which in actuality is non-existent, arises because the analysis places the neutral axis at the plastic centroid. The concrete in tension produces no force while the compressed concrete develops a force. The reinforcement develops both tensile and compressive forces, but an unbalanced compressive force remains on the net cross section. By adjusting the strains until they produce no thrust the neutral axis could be properly located.

EXTERN, a subroutine described later, calculates a thrust in the bars and joints directly from the average strains ϵ_{BARi}^{AVG} and ϵ_{JTi}^{AVG}. These are correct values and the strain distributions in the method described above are adjusted until the thrusts computed in this manner agree within acceptable limits, with those given by EXTERN. The corresponding moments are then assumed also to be correct. Returning to the example of the beam subjected to pure bending, EXTERN would calculate a thrust equal to zero since the ends of the beam have not been displaced in an axial direction. DEFORM would then use the values calculated by EXTERN to modify the fiber strains until the computed thrusts are within acceptable limits, equal to zero. This correction is required only if the strain changes sign between the outer and inner faces of the cross section. The problem does not exist if the entire section is in either tension or compression.

5. <u>Subroutine EXCITE</u>:

The blast and soil spring forces acting upon the structure are computed by EXCITE. Deformations in the springs are used to determine spring forces and a pressure-time diagram is used to determine blast pressures.

LOCATE, a subroutine discussed later, calculates the total time that has elapsed since the wave first engulfed each of the masses on the structure. Using a pressure-time diagram such as Figure 11 and the elapsed time since initial contact of the mass by the blast wave, it is possible to determine the pressure level acting on mass i. The pressure from the diagram is the vertical pressure acting downward on mass i at the time in question. The pressure on mass i is assumed to extend over half a bar length on each side of it. To obtain the vertical blast force on mass i the pressure on that mass is multiplied by the horizontal projections of half of bars i-1 and i. Therefore,

$$\text{FORCE}_{yi}^{\text{BLAST}} = \text{PRESSURE}_i \left(\frac{L_{i-1}}{2} \cos \alpha_{i-1} + \frac{L_i}{2} \cos \alpha_i \right) \tag{32}$$

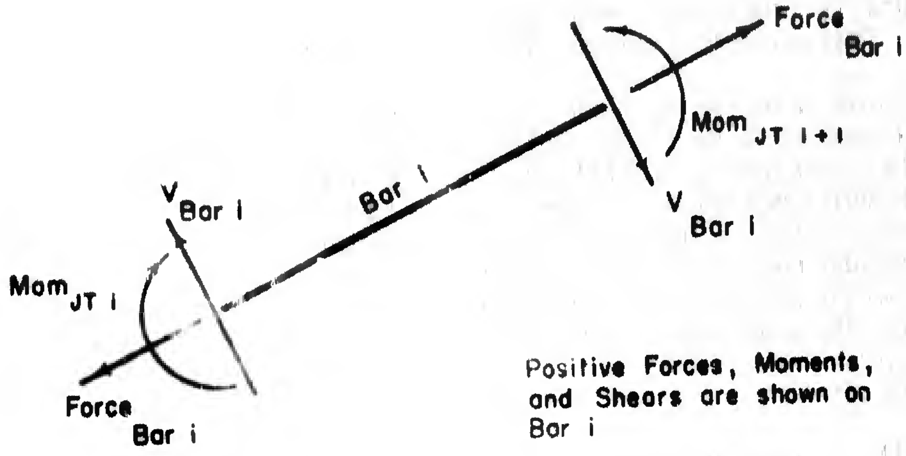


FIGURE 10. INTERNAL STRUCTURAL RESISTING FORCES

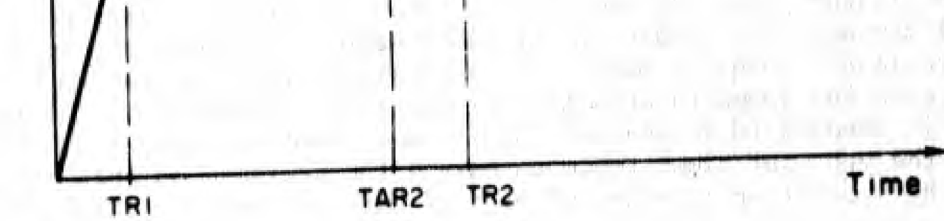


FIGURE 11. IDEALIZED BLAST LOAD FUNCTION

where $FORCE_{yi}^{BLAST}$ is the concentrated blast force acting downwards on mass i and $PRESSURE_i$ is the vertical blast pressure acting on mass i. The horizontal blast force on mass i is computed in essentially the same manner from the horizontal free-field [illegible] pressures, which are assumed to be equal to a constant (RATIO) times the corresponding vertical free-field pressures. Thus, the horizontal blast force on mass i is the pressure multiplied by the vertical projections of half of bars i-1 and i,

$$FORCE_{xi}^{BLAST} = RATIO \cdot PRESSURE_i \left(\frac{L_{i-1}}{2} \; SIN \; \alpha_{i-1} + \frac{L_i}{2} \; SIN \; \alpha_i \right) \quad (33)$$

where $FORCE_{xi}^{BLAST}$ is the concentrated blast force acting in the x direction on mass i and RATIO is the ratio of horizontal to vertical blast pressures in the soil.

The pressure-time diagram, as shown in Figure 11, is read into the computer using the following variables:

A1 - first pressure amplitude

A2 - second pressure amplitude

TR1 - time at which pressure attains amplitude A1

TAR2 - time at which second pressure wave, A2, arrives

TR2 - time at which pressure attains amplitude A2.

If A1 = A2 a step pulse of infinite duration results. If TAR2 = TR2, a straight line connecting A1 and A2 results. These variations of the basic pressure pulse are shown in Figure 12. Necessary restrictions on choice of TR1, TAR2 and TR2 are that

$TR1 \leq TAR2$

$TAR2 \leq TR2.$

The resistance of the soil surrounding the structure is approximated by springs attached to the masses. Since most soil has little if any tensile strength, the springs are assumed to act only in compression. As noted earlier, the soil resistance is assumed to be linearly elastic. However, in anticipation of extending the program to treat multilinear soil resistance funtions, the initial elastic slope is defined by the spring stiffness, k_i, as follows:

$$k_i = \frac{FORCYY(I)}{DEFYY(I)} \quad (34)$$

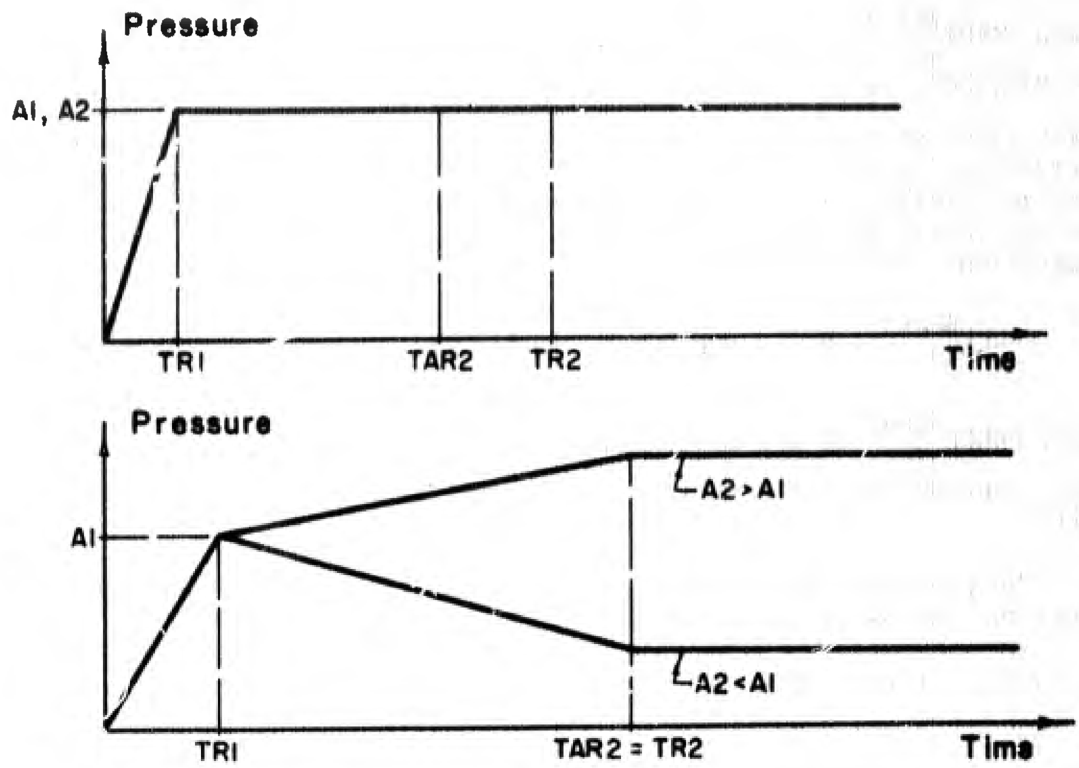


FIGURE 12. VARIATIONS OF BLAST LOAD FUNCTIONS

where FORCYY(I) is the yield pressure of the springs at mass i and DEFYY(I) is the yield deformation of the springs at mass i. Since an elastic spring is being used, DEFYY(I) has no physical meaning and is used only to define k_i. If DEFYY(I) = 1. is read into the computer, then k_i = FORCYY(I). Figure 13 is the pressure-deformation diagram of the springs used to approximate the soil.

The vertical force on mass i from the vertical soil spring is

$$FORCE_{yi}^{SPRING} = k_i \, \Delta y_i \left(\frac{L_{i-1}}{2} \cos \alpha_{i-1} + \frac{L_i}{2} \cos \alpha_i \right) \tag{35}$$

and the horizontal force on the mass from the horizontal spring is

$$FORCE_{xi}^{SPRING} = k_i \, \Delta x_i \left(\frac{L_{i-1}}{2} \sin \alpha_{i-1} + \frac{L_i}{2} \sin \alpha_i \right) \tag{36}$$

The values of Δy_i and Δx_i are the total deformations in the springs and are equal to the total coordinate change of mass i as calculated by BETA.

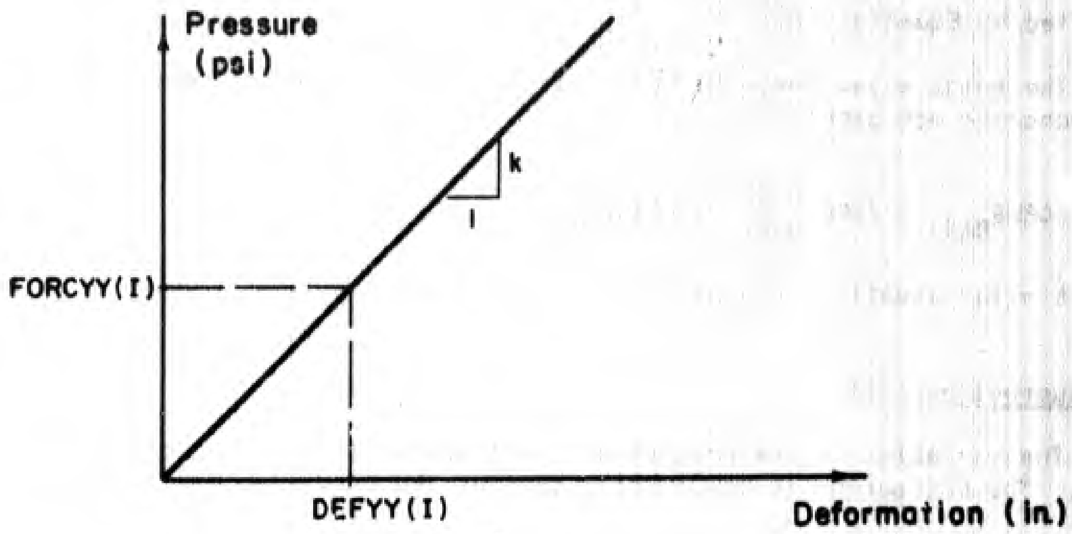


FIGURE 13. SOIL RESISTANCE FUNCTION

6. Subroutine EXTERN:

The purpose of EXTERN has already been discussed in some detail in the section on DEFORM. In EXTERN, the average bar and joint strains are used to calculate thrusts which are then used in DEFORM to correctly locate the neutral axis of the section, and thence, the bending moment on the section.

The axial force in the concrete of bar i is given by

$$FORCE^{CONC}_{BAR\,i} = \sigma^{CONC\ AVG}_{BAR\,i} \cdot H \tag{37}$$

where H is the section depth and $\sigma^{CONC\ AVG}_{BAR\,i}$ is the concrete stress which is obtained from Figure 8 to be consistent with $\epsilon^{AVG}_{BAR\,i}$ from Equation (12).

Similarly, axial force in the steel reinforcement is

$$FORCE^{STEEL}_{BAR\,i} = \sigma^{STEEL\ AVG}_{BAR\,i} \cdot A_{TOTAL} \tag{38}$$

where $\sigma_{BAR\,i}^{STEEL\;AVG}$ is the steel stress which is obtained from Figure 9 using $\epsilon_{BAR\,i}^{AVG}$ from Equation (12). If the bar is in compression A_{TOTAL} must be modified by Equation (28).

The total axial force in bar i is the sum of the axial forces carried by the concrete and steel, or

$$FORCE_{BAR\,i} = FORCE_{BAR\,i}^{CONC} + FORCE_{BAR\,i}^{STEEL} \tag{39}$$

Similar equations can also be developed for the axial forces in joint i.

7. Subroutine INIT:

The variables in the program are initialized to their proper values by INIT. The subroutine is called only once at the beginning of the program.

8. Subroutine LOCATE:

The purpose of this subroutine is to locate the advancing pressure pulse with respect to the model under study. Two versions of LOCATE were developed. One version was developed to study the special case of a horizontal wave, propagating vertically downward as shown in Figure 14; the other version considered the more general case of an inclined wave propagating horizontally across the structure as shown in Figure 15. In its limit, the latter case can be made to approximate the former, which is a special case developed primarily to facilitate the checking of the computer program. A symmetrical structural system subjected to the wave generated by the vertical version of LOCATE responds symmetrically; this fact substantially simplified the program checking studies.

If a study of structural response to unsymmetrical loading is of interest, the second version of LOCATE should be used. In any case, only one of the versions of this subroutine should be compiled with the other subroutines to build a complete program.

Both versions of LOCATE use the coordinate of mass i to determine the length of time that the pressure has been acting upon that mass. The vertical version of LOCATE uses y_i of mass i for location purposes, while the horizontal version uses x_i. The location method for the horizontal version is similar to that of the vertical and will not be discussed here.

During a time interval Δt, a wave propagating downward across the structure moves a distance Δy which is determined by

$$\Delta y = \text{VERTICAL VELOCITY} \times \Delta t \tag{40}$$

where the vertical velocity of the wave front is read into the computer as part of the input data. The wave makes contact with the top of the structure at time t=0; thus, at this instant, the wave front is at the highest mass on the structure, and is designated as

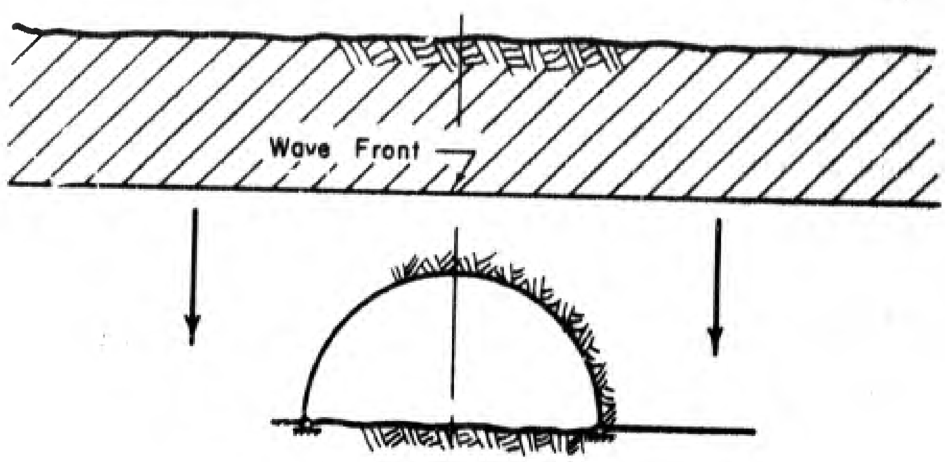


FIGURE 14. BURIED ARCH UNDER VERTICAL SHOCK FRONT

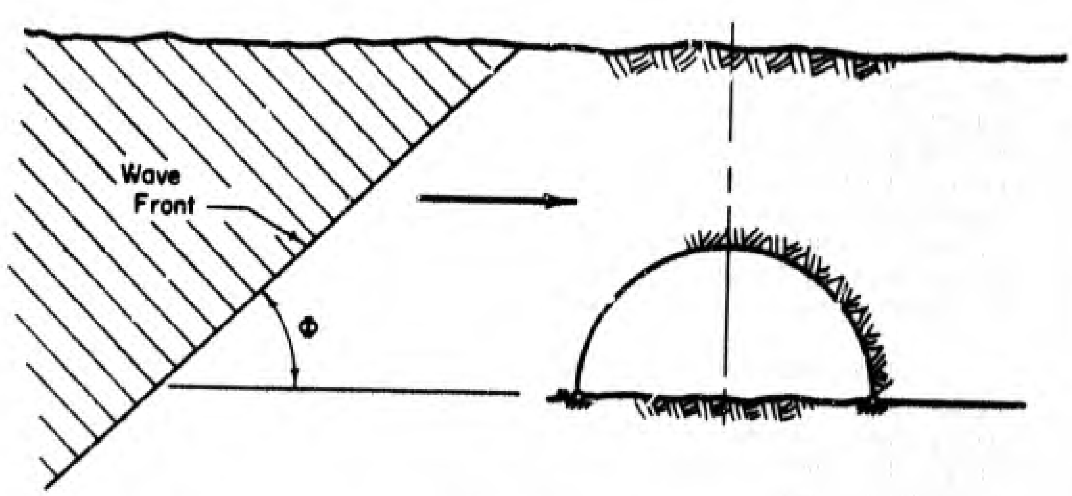


FIGURE 15. BURIED ARCH UNDER INCLINED SHOCK FRONT

$$\text{WAVE FRONT}^{t=0} = y_i^{MAX} \tag{41}$$

At time $t = 0+\Delta t$, the location of the front is

$$\text{WAVE FRONT}^{t=0+\Delta t} = \text{WAVE FRONT}^{t=0} - \Delta y$$

or, in general, at any time t=t,

$$\text{WAVE FRONT}^{t=t} = \text{WAVE FRONT}^{t=t-\Delta t} - \Delta y \tag{42}$$

To determine the amount of time that the wave has been acting on mass i, the distance between mass i and the wave front, $\delta y_i^{t=t}$, must be determined.

$$\delta y_i^{t=t} = y_i^{t=t} - \text{WAVE FRONT}^{t=t} \tag{43}$$

If this value is negative, the wave front is above mass i and the computer value of T(I), the elapsed time since wave contact with the mass, is set equal to zero. If $\delta y_i^{t=t}$ is positive, the value of T(I) is obtained by

$$T(I) = \delta y_i^{t=t} / \text{(VERTICAL VELOCITY)} \tag{44}$$

The values of T(I) computed in LOCATE in this manner are used in EXCITE. The pressures on the several masses are determined at times T(I) from a pressure-time diagram that is stored by the computer in that subroutine.

9. <u>Subroutine YIELD</u>:

The time histories of the strains in the various parts of the structure are computed and stored in YIELD. The histories of the strains in both the concrete fibers and in the steel reinforcement are necessary because neither of the materials is purely elastic, the determination of stress from strain in a vibration problem, where there is periodic loading and unloading, is impossible without a complete strain history. Such histories are necessary so that the accumulated plastic sets can be properly considered when stresses corresponding to computed strains are read from stress-strain diagrams such as those shown in Figures 8 and 9.

YIELD checks every strain in the concrete fibers and the reinforcing steel of the several bars and joints of the model to determine if and when the strain exceeds the yield strain for the material concerned. If the yield strain has been exceeded it calculates the plastic set, or permanent deformation, by subtracting the yield strain from the total strain. In bar i, the plastic set in fiber j of the concrete is given by

$$\text{PLASTIC SET}^{j}_{BAR\,i} = \epsilon^{j}_{BAR\,i} - \epsilon^{CONC}_{y} \tag{45}$$

Similarly, in the outer and inner reinforcing steel the plastic sets are, respectively

$$PLASTIC\ SET_{BAR\,I}^{OUTER\ STEEL} = \epsilon_{BAR\,I}^{OUTER\ STEEL} - \epsilon_{y}^{STEEL} \quad (46)$$

$$PLASTIC\ SET_{BAR\,I}^{INNER\ STEEL} = \epsilon_{BAR\,I}^{INNER\ STEEL} - \epsilon_{y}^{STEEL} \quad (47)$$

where ϵ_y^{CONC} and ϵ_y^{STEEL} are the yield strains in concrete and steel.

The subroutine checks the strains before BETA starts a new time increment and modifies the plastic sets in accordance with the last computed strains.

SECTION IV

ILLUSTRATIVE APPLICATION OF PROGRAM

1. Description of Soil-Structure System:

To illustrate the applicability of the computer program developed in this study, it was used to investigate the influence of localized variations in soil resistance on the blast pressure that is required to damage a typical buried, pin-ended, reinforced concrete arch.

The arch that was analyzed is illustrated in Figure 16(a). It had a radius of 15 ft. and a total thickness of 13.5 inches, which corresponds to a thickness-radius ratio of 0.075. The central angle of the arch was 180°, and it was reinforced with 1.0 percent steel on each face. The steel was placed circumferentially, 1 1/2 inches from each face of the section. A cross section through the arch is shown in Figure 16(b), and the stress-strain diagrams for the concrete and steel were idealized as shown in Figures 16(c) and (d).

For purposes of analysis, a section of the arch 1.0 inch long was considered. This soil-arch system was represented, as shown in Figure 17(a), by a six-bar system, with the masses, resistances, and forces concentrated at the node points. Each bar was 93.175 inches long, and had the same cross section as did the arch being represented.

All soil springs were assumed to be linearly elastic and, at any given mass point, both the horizontal and vertical springs were assumed to have the same stiffness. The basic soil springs stiffness of all springs, against which the comparative effect studies were made, was computed as described in Section III to be consistent with a foundation modulus of 50 psi per inch of deformation.

The masses were determined on the assumption that the unit weight of the surrounding soil was 100 pcf, and that soil within one arch radius of the arch vibrated with the arch. Thus, each mass was computed from the weight of the "effective" adjacent soil, to be 1.301 lb-sec^2/in.

The system was subjected to a pressure pulse of the form shown in Figure 17(b). This pressure pulse was assumed to have a horizontal front and to propagate downward through the soil at a seismic velocity of 4000 fps.

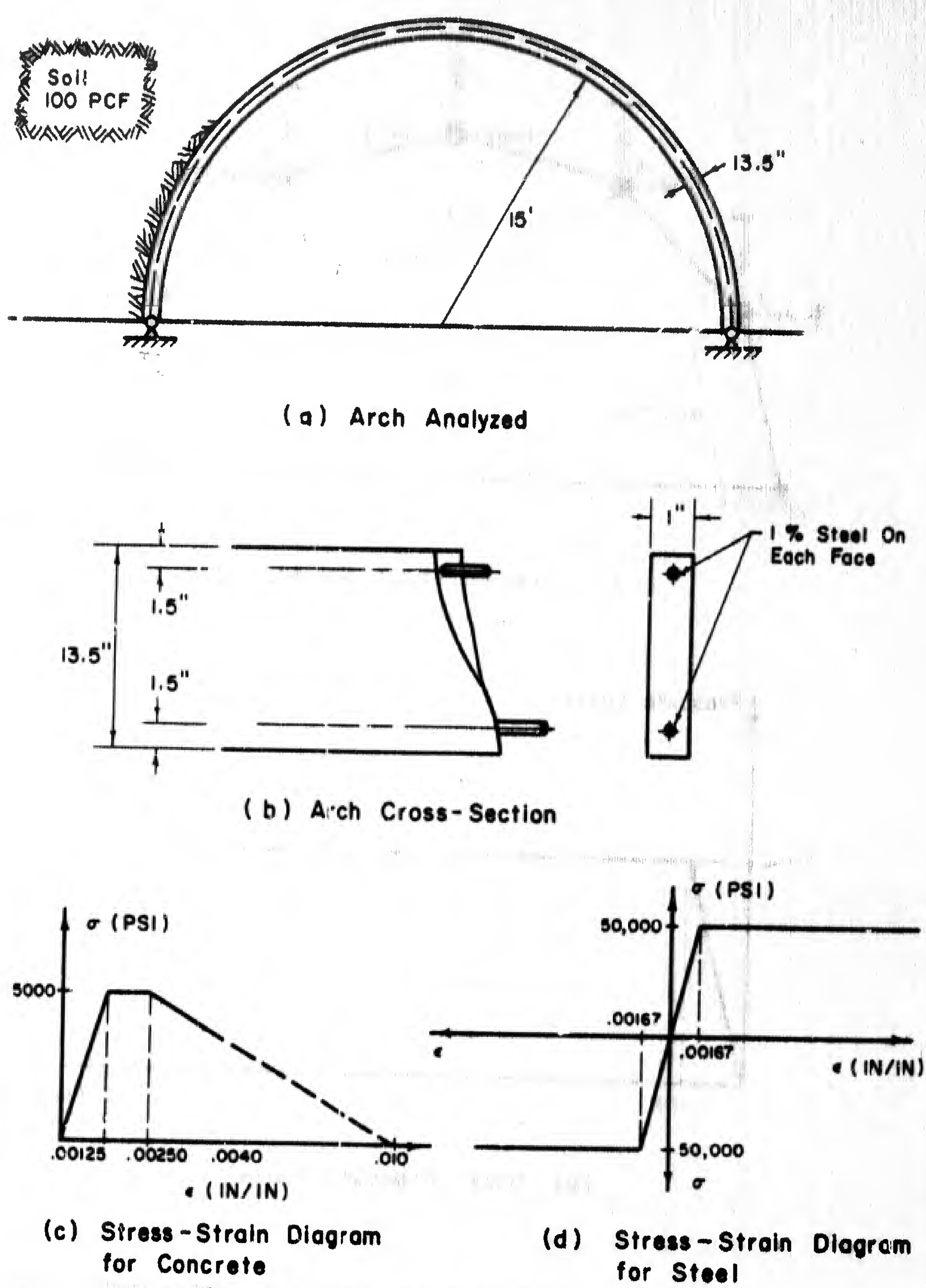
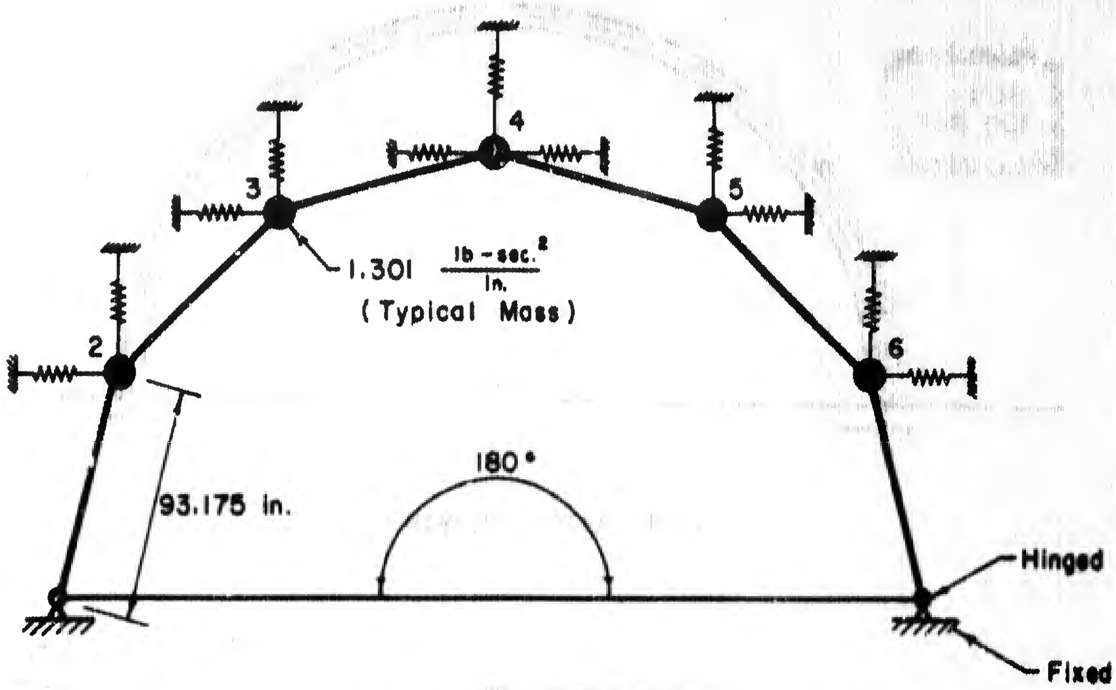
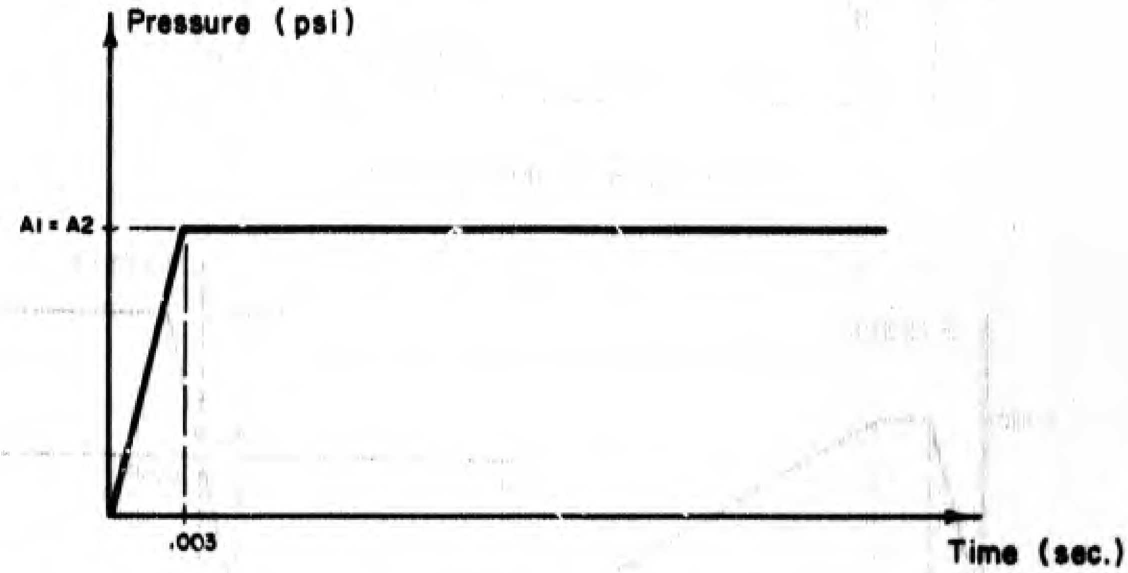


FIG. 16. DESCRIPTION OF ARCH UNDER STUDY



(a) Lumped Mass System



(b) Blast Pressure Pulse

FIG. 17. SOIL-STRUCTURE SYSTEM IDEALIZED FOR ANALYSIS.

2. Influence of Variations in Soil Resistance:

The system as previously described was first analyzed to determine the blast pressure level that was required to produce failure under a uniform soil resistance corresponding to a foundation modulus of 50 psi/in. of deformation. Failure was defined, as described in Section III, to have occurred when one of the following conditions existed.

(a) Yield hinges developed on two sections in the model,

(b) Concrete crushing occurred in fibers at two sections in the model,

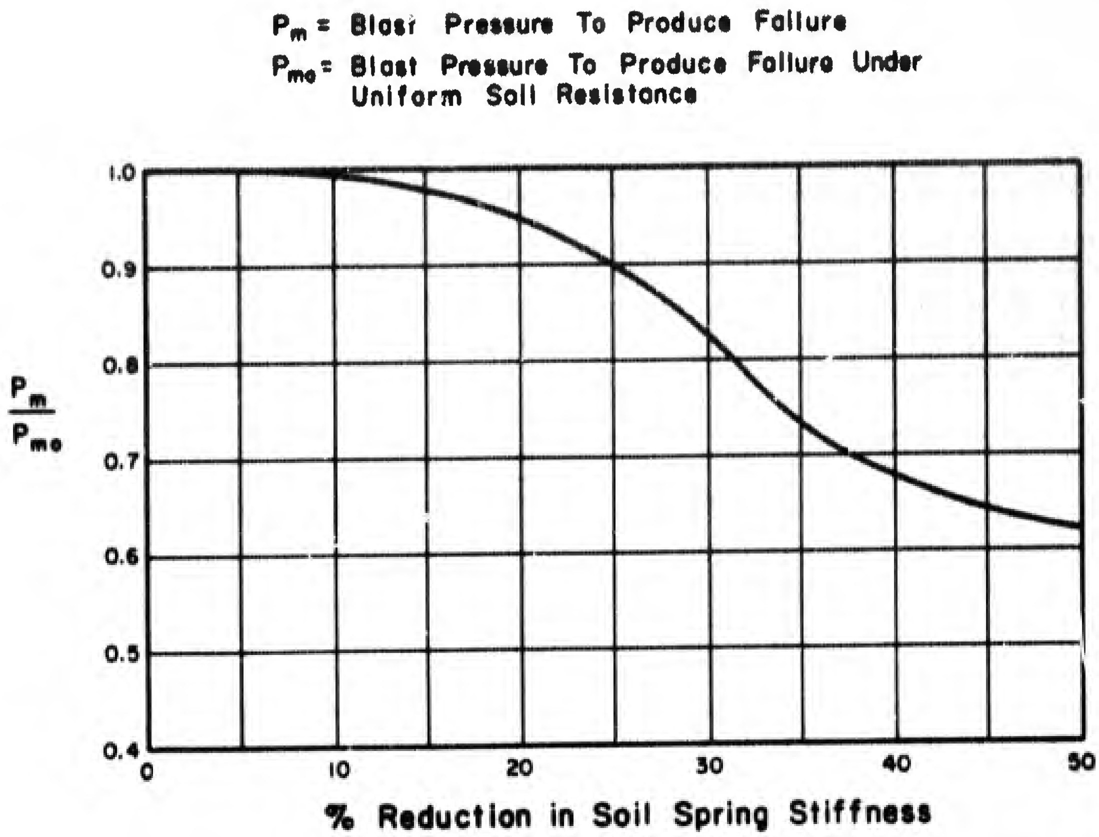
(c) A yield hinge and concrete crushing developed at the same or at two different sections in the model.

This basic blast failure pressure was found to be 95.5 psi.

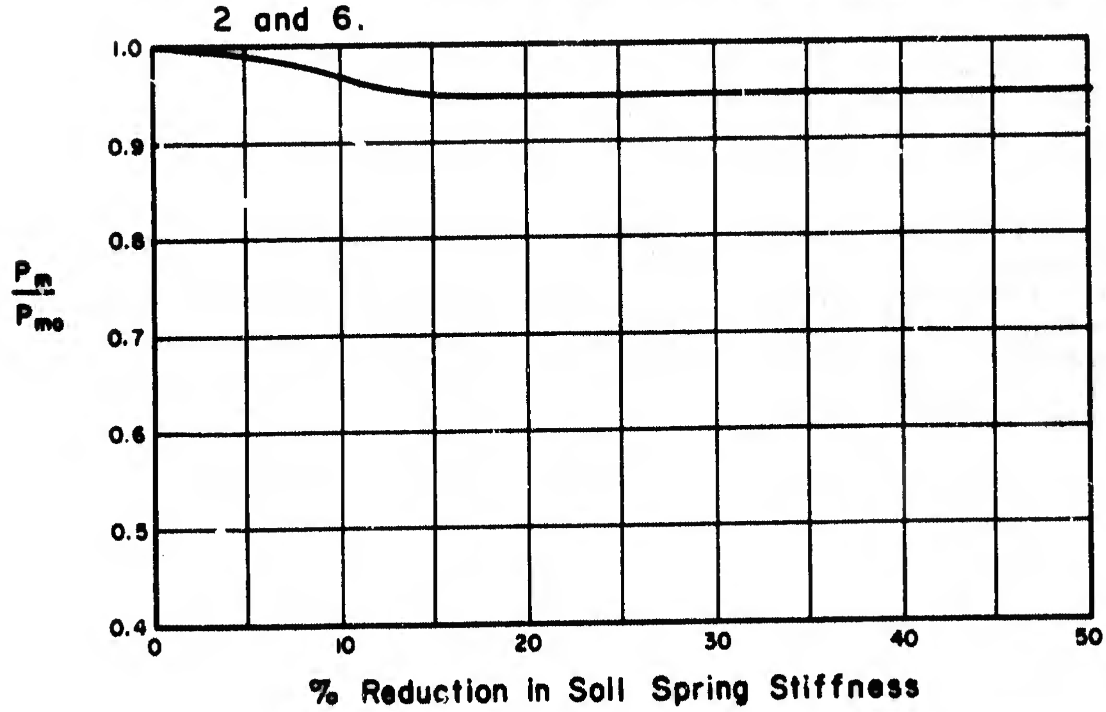
Analyses were then carried out to determine the extent to which this blast failure pressure would be reduced because of equal reductions in the soil spring stiffnesses at mass points 2 and 6, the other soil spring stiffnesses remaining unchanged. The results of these analyses are shown in Figure 18(a).

Similar analyses were carried out to determine the influence on the blast failure load of varying the soil spring stiffnesses at mass points 3 and 5, the other stiffness remaining unchanged. The results of these studies are shown in Figure 18(b).

The results portrayed in Figure 18 are self-explanatory. It is appropriate, however, to point out that these data are indicative of the kind of information that can be obtained through the use of the computer program that was developed in this project. If properly employed, it could be used to yield information that would be of significant value in the evaluation of hardness of existing facilities as well as in the design and construction of similar facilities in the future.



(a) Influence of Variations in Soil Resistances at Mass Points 2 and 6.



(b) Influence of Variations in Soil Resistances at Mass Points 3 and 5.

FIG. 18. REDUCTION IN BLAST FAILURE PRESSURE AS A FUNCTION OF LOCALIZED REDUCTIONS IN SOIL RESISTANCE.

APPENDIX

The following pages contain a reproduction of the actual computer printout of the complete program that was developed in this project. For ease in studying it, an alphabetic listing of all FORTRAN variables used in the program, together with their definitions, is presented in Sub-section 2. Similarly, the basic input data are summarized in Sub-section 3.

1. Computer Program Printout:

a. Main Program

```
      DIMENSION PALFA(10),PX(11),PY(11),X(11),Y(11),DBARL(10),EPSBAR(10)
     1,TEPBAR(10),DALFA(10),DANJT(11),CRVJT(11),CRVBAR(10),
     2 TFEPSB(10,20),EPSJT(11),              TFEPSJ(11,20)          ,TS
     3EPBT(10),            TSEPBB(10)          ,TSEPJT(11)          ,TS
     4EPJB(11)               ,PLSETB(10,20),FSIGB(10,20)
     ODIMENSION PLSETJ(11,20),FSIGJ(11,20),CFORCB(10),CMOMB(10),CFORCJ(1
     11),CMOMJ(11),SEPYPT(11),SEPYPC(11),ESEPBT(10),SPSTBT(10),SFORBT(10
     2),SPSTBB(10),ESEPBB(10),SFORBB(10),SPSTJT(11),ESEPJT(11),SFORJT(11
     3),ESEPJB(11),SPSTJB(11),SFORJB(11),FORCB(10),BMOMB(10),FORCJ(11),B
     4MOMJ(11)              ,VB(10),WFRTX(11),XDIFFX(11)
     ODIMENSION              FORCY(11),DEFYY(11),DEFY(11),DEFX1(11),DEFX2(11
     1)
     2,A(11),FY(11),FX1(11),FX2(11),T(11),EPSETB(10),EFORCB(10),TEPJT(11
     3),EPSETJ(11),EFORCJ(11),ESPSTB(10),EESEPB(10),EFORSB(10),ESPSTJ(11
     4),EESEPJ(11),EFORSJ(11),COUNTB(10),FORDFB(10),DIFEPB(10)
      DIMENSION             CMASS(10),FV(10),FH(10),VV(10),VH(10),FV1(10),FV
     12(10),FH1(10),FH2(10),VV1(10),VV2(10),VH1(10),VH2(20),DX(10),DY(10
     2),DDX(10),DDY(10),ALFA(10),DDXEND(10),DDYEND(10)
     3,DXEND(10),DYEND(10)          ,FORDFJ(11),DIFEPJ(11),BLAST1(11),BLAST
     42(11),BLASTY(11),PDDX(10),PDDY(10),LC(10),JC(11),LY(10),JY(11)
      DIMENSION CHKY1(10),CHKY2(10),XORIG(11),YORIG(11)
      DIMENSION DELX(10),DELY(10),TDELX(10),TDELY(10)
C
     OCOMMON PALFA,PX,PY,X,Y,DBARL,EPSBAR,TEPBAR,DALFA,DANJT,CRVJT,CRVBA
     1R,       TFEPSB,EPSJT,          TFEPSJ,          TSEPBT          ,TSEPBB
     2        ,TSEPJT           ,TSEPJB           ,PLSETB,FSIGB           ,PLSETJ,FSIGJ,
     3CFORCB,CMOMB,CFORCJ,CMOMJ,SEPYPT,SEPYPC,ESEPBT,SPSTBT,SFORBT,SPSTB
     4B,ESEPBB,SFORBB,SPSTJT,ESEPJT,SFORJT,ESEPJB,SPSTJB,SFORJB,FORCB,BM
     5OMB,FORCJ,BMOMJ,N,NN,BARL,NFIBRE,D,DPRIM,AS,EC,CEPSY,CEPSCR,CEPSU,
     6CEPSO,ES,SEPSY           ,VB,WFRTX,XDIFFX
     OCOMMON A1,A2,TR1,TAR2,TR2,PHEE                    ,FORCY,DEFYY,DEFY,DEFX1,D
     1EFX2                                              ,A,FY,FX1,FX2,T,SIZVE
     2L,Q,DELTIM,EPSETB,EFORCB,TEPJT,EPSETJ,EFORCJ,ESPSTB,EESEPB,EFORSB,
     3ESPSTJ,EESEPJ,EFORSJ,COUNTB,FORDFB,DIFEPB,FORDFJ,DIFEPJ
      COMMON HGT,CMASS,FV,FH,VV,VH,FV1,FV2,FH1,FH2,VV1,VV2,VH1,VH2,GAMMA
     1S,DX,DY,DDX,DDY,ALFA,DDXEND,DDYEND             ,DXEND,DYEND,B,ALERB,
     2       TIME,RATIO,ALERR,BLAST1,BLAST2,BLASTY
      COMMON                       PDDX,PDDY,KOUNT,NPRINT,LC,JC,LY,JY,DUMMY,
     2CHKY1,CHKY2,XORIG,YORIG
      COMMON DELX,DELY,TDELX,TDELY,YCOUNT
C
      RIT 7, 100,N,BARL
```

```
      NN=N-1
      RIT 7,103,A1,A2,TR1,TAR2,TR2
      RIT 7,103,RATIO
      RIT 7,103,(FORCY(I),I=2,NN)
  390 RIT 7,103,(DEFYY(I),I=2,NN)
C
C     DEFINE INITIAL STRUCTURAL CONFIGURATION
      RIT 7,103,SIZVEL
      RIT 7,103,DELTIM,TFINAL
      RIT 7,100,NFIBRE,ALERR
      RIT 7,102,D,DPRIM,AS
      RIT 7,103,EC,CEPSY,CEPSCR,CEPSU,CEPSO
      RIT 7,103,ES,SEPSY
      RIT 7,101,(PALFA(I),I=1,NN)
      DO 10 I=1,NN
   10 PALFA(I)=PALFA(I)*.01745
      PX(1)=0.
      PY(1)=0.
      DO 11 I=2,N
      II=I-1
      PX(I)=PX(II)+BARL*COS(PALFA(II))
   11 PY(I)=PY(II)+BARL*SIN(PALFA(II))
      DO 12 I=1,N
      X(I)=PX(I)
      Y(I)=PY(I)
      XORIG(I)=X(I)
   12 YORIG(I)=Y(I)
      RIT 7,101,B,ALERB
      RIT7,101,PHEE
      RIT 7,101, GAMMAS,HGT
      RIT 7,100,NPRINT
      WOT 6,231
      WOT 6,232
      WOT 6,222, N
      WOT 6,233
      WOT 6,227,(I,I=1,N)
      WOT 6,228,(X(I),I=1,N)
      WOT 6,234
      WOT 6,227,(I,I=1,N)
      WOT 6,228,(Y(I),,I=1,N)
      WOT 6,235
      WOT 6,236
      WOT 6,237,B
      WOT 6,238,DELTIM
      WOT 6,239
      WOT 6,240
      E=HGT*BARL
      WOT 6,223,E
      E=1728.*GAMMAS
      WOT 6,224,E
      WOT 6,225
      WOT 6,226
      WOT 6,227,(I,I=2,NN)
      WOT 6,228,(FORCY(I),I=2,NN)
      WOT 6,229
      WOT 6,230
      WOT 6,227,(I,I=2,NN)
      WOT 6,228,(DEFYY(I),I=2,NN)
      WOT 6,200
```

```
      WOT 6,201
      WOT 6,203,D,AS
      E=2.*DPRIM
      WOT 6,204,E
      WOT 6,205
      WOT 6,206
      WOT 6,207
      WOT 6,208
      WOT 6,209,ES
      SIGY=ES*SEPSY
      WOT 6,210,SIGY
      WOT 6,211
      WOT 6,209,EC
      SIGY=EC*CEPSY
      WOT 6,210,SIGY
      WOT 6,212,CEPSY
      WOT 6,213,CEPSCR
      WOT 6,214,CEPSU
      WOT 6,215
      WOT 6,216
      WOT 6,217,A1
      WOT 6,218,A2
      WOT 6,219,TR1
      WOT 6,220,TR2
      WOT 6,221,TR3
C
      CALL FTRAP
      CALL INIT
      CALL DEFORM
      CALL BETA
      CC=1.
      DO 804 I=1,NN
      PX(I)=X(I)
      PY(I)=Y(I)
  804 ALFA(I)=PALFA(I)
  802 IF (TFINAL-TIME) 800,800,801
  801 CALL LOCATE
      Q=1.
      CALL DEFORM
      CALL EXCITE
      CALL BETA
      GO TO 802
  100 FORMAT (I3,E12.4)
  101 FORMAT (5E12.4)
  102 FORMAT (3E12.4)
  103 FORMAT (5E12.4)
  200 FORMAT (1H0,10X,19H SECTION PROPERTIES)
  201 FORMAT (11X,19H ******* **********,//)
  203 FORMAT (27H THE SECTION HAS A DEPTH OF,F6.2,14HINCHES AND HAS,F7.4
     1,37HSQ IN OF STEEL PER INCH WIDTH OF ARCH)
  204 FORMAT (1H0,49H THE STEEL IS EQUALLY DISTRIBUTED IN  TWO LAYERS ,F
     16.2,14H INCHES APART.,/)
  205 FORMAT (52H THE ENTIRE SECTION IS SYMMETRICAL ABOUT ITS CENTER.,/)
  206 FORMAT (1H0,10X,20H MATERIAL PROPERTIES)
  207 FORMAT (11X,20H ******** ********** ,//)
  208 FORMAT (1H0,18H REINFORCING STEEL)
  209 FORMAT (23H MODULUS OF ELASTICITY=,F12.2,3HPSI)
  210 FORMAT (14H YIELD STRESS=,F12.2,3HPSI)
  211 FORMAT (1H0,9H CONCRETE)
```

```
212 FORMAT (14H YIELD STRAIN=,F9.5,5HIN/IN)
213 FORMAT (17H CRITICAL STRAIN=,F9.5,5HIN/IN)
214 FORMAT (17H ULTIMATE STRAIN=,F9.5,5HIN/IN)
215 FORMAT (1H0,10X,26H PRESSURE PULSE PROPERTIES)
216 FORMAT (11X,26H **************************,//)
217 FORMAT (4H P1=,F9.2,3HPSI)
218 FORMAT (4H P2=,F9.2,3HPSI)
219 FORMAT (13H RISE TIME 1=,F9.5,7HSECONDS)
220 FORMAT (16H ARRIVAL TIME 2=,F9.5,7HSECONDS)
221 FORMAT (13H RISE TIME 2=,F9.5,7HSECONDS)
222 FORMAT (29H THE ARCH IS APPROXIMATED BY ,I3,6H BARS.,/)
223 FORMAT (19H A RADIAL DEPTH OF ,F7.2,52H INCHES OF SOIL IS ASSUMED
   1TO RESPOND WITH THE ARCH.)
224 FORMAT (26H THE SOIL HAS A DENSITY OF,F7.2,5H PCF.,/)
225 FORMA  (10X,22H SOIL STRENGTH-PSI/IN.)
226 FORMAT (10X,14H *************,/)
227 FORMAT (3H I=,I3,9I13)
228 FORMAT (11F10.2)
229 FORMAT (1H0,33H YIELD DEFORMATION OF SPRINGS-IN.)
230 FORMAT (1H ,29H *****************************,/)
231 FORMAT (1H ,10X,25H STRUCTURAL CONFIGURATION,/)
232 FORMAT (1H ,10X,25H ********** *************,/)
233 FORMAT (14H X COORDINATES,/)
234 FORMAT (14H Y COORDINATES,/)
235 FORMAT (1H0,22H NUMERICAL INTEGRATION,/)
236 FORMAT (1H ,22H ********* ***********,/)
237 FORMAT (6H BETA=,F6.4)
238 FORMAT (15H TIME INTERVAL=,F10.6,8H SECONDS)
239 FORMAT (1H0,15X,16H SOIL PROPERTIES,/)
240 FORMAT (11X,16H **** **********,/)
    CONTINUE
    END
```

b. Subroutine BETA

```
 DIMENSION AND COMMON STATEMENTS ON FIRST PAGE OF
COMPUTER PRINT-OUT ARE TO BE ADDED HERE.

      SUBROUTINE BETA
  130 FORMAT (E10.4,1X,E10.4)
  132 FORMAT (E10.4)
C
  120 FORMAT(//,13H             TIME=,E10.5,13H        SECONDS,/)
  121 FORMAT (91H   I      X(I)          Y(I)         DELX(I)      DELY(I)       DX(I
     1)         DY(I)        DDX(I)       DDY(I)    )
  122 FORMAT (I3,1X,E10.4,1X,E10.4,1X,E10.4,1XE10.4,1X,E10.4,1X,E10.4,1X
     1,E10.4,1X,E10.4)
  123 FORMAT(55H I   FORCB(I)       VB(I)        MOMJ(I)      DEFORM        BETA    )
  124 FORMAT (91H  *       ****          ****        *******      *******       ****
     1*        *****        ******       ******    ,/)
  125 FORMAT(56H**   **********    *******     *********     ********      ******
     1 ,/)
  126 FORMAT(/,38X,16HNUMBER OF CYCLES)
  127 FORMAT ( 32H      I,FV1,FV2,VV1,VV2,FY,BLASTY )
  128 FORMAT (31H       I,FH1,FH2,VH1,VH2,FX1,FX2 )
  129 FORMAT (21H       I,BLAST1,BLAST2 )
C
      BCOUNT=0.
      DO 5 I=2,NN
      TDELY(I)=TDELY(I)-DELY(I)
      TDELX(I)=TDELX(I)-DELX(I)
    5 CMASS(I)=(HGT*(BARL**2.)*GAMMAS+.0869*BARL*D)/386.4
   45 DO 10 I=1,NN
      FV(I)=FORCB(I)*SIN(ALFA(I))
      FH(I)=FORCB(I)*COS(ALFA(I))
      VV(I)=VB(I)*COS(ALFA(I))
   10 VH(I)=VB(I)*SIN(ALFA(I))
      DO 20 I=1,NN
      IF ( ALFA(I)) 1,2,3
    1 FV1(I)=-FV(I)
      FV2(I)=FV(I)
      FH1(I)=-FH(I)
      FH2(I)=FH(I)
      VV1(I)=VV(I)
      VV2(I)=-VV(I)
      VH1(I)=-VH(I)
      VH2(I)=VH(I)
      GO TO 20
    2 FV1(I)=0.
      FV2(I)=0.
      FH1(I)=-FH(I)
      FH2(I)=FH(I)
      VV1(I)=VV(I)
      VV2(I)=-VV(I)
      VH1(I)=0.
      VH2(I)=0.
      GO TO 20
    3 FV1(I)=-FV(I)
      FV2(I)=FV(I)
      FH1(I)=-FH(I)
```

```
      FH2(I)=FH(I)
      VV1(I)=VV(I)
      VV2(I)=-VV(I)
      VH1(I)=-VH(I)
      VH2(I)=VH(I)
   20 CONTINUE
      BCOUNT=BCOUNT+1.
      IF ( BCOUNT-8. ) 309,305,305
  305 TIME=TIME - DELTIM
      DO 308 I=1,N
      WFRTX(I)=WFRTX(I)+SIZVEL*DELTIM
      XDIFFX(I)=Y(I)-WFRTX(I)
      IF ( XDIFFX(I) ) 306,306,307
  306 T(I) = 0.
      GO TO 308
  307 T(I)=XDIFFX(I)/SIZVEL
  308 CONTINUE
      DELTIM=.5*DELTIM
      RETURN
  309 DO 30 I=2,NN
      II=I-1
   60 FV(I)=-FV2(II)-FV1(I)-VV2(II)-VV1(I)+FY(I)+BLASTY(I)
      FH(I)=-FH2(II)-FH1(I)-VH2(II)-VH1(I)-FX1(I)+FX2(I)+BLAST1(I)+BLAST
     12(I)
      PDDX(I)=DDXEND(I)
      PDDY(I)=DDYEND(I)
      DDXEND(I)=FH(I)/CMASS(I)
      DDYEND(I)=FV(I)/CMASS(I)
   30 CONTINUE
      DO 25 I=2,NN
      AQ=ABSF(ALERB*DDXEND(I) )
      AX=ABSF(PDDX(I)-DDXEND(I) )
      IF ( AQ-AX ) 21,22,22
   21 IF ( AX-.1 ) 22,22,26
   22 AQ=ABSF(ALERB*DDYEND(I))
      AY=ABSF(PDDY(I)-DDYEND(I))
      IF ( AQ-AY ) 24,25,25
   24 IF ( AY-.1 ) 25,25,26
   25 CONTINUE
      GO TO 42
   26 DO 23 I=2,NN
      DELX(I)=DX(I)*DELTIM+(.5-B)*DDX(I)*(DELTIM**2.)+B*DDXEND(I)*(DELTI
     1M**2.)
      DXEND(I)=DX(I)+.5*DDX(I)*DELTIM+.5*DDXEND(I)*DELTIM
      DELY(I)=DY(I)*DELTIM+(.5-B)*DDY(I)*(DELTIM**2.)+B*DDYEND(I)*(DELTI
     1M**2.)
   23 DYEND(I)=DY(I)+.5*DDY(I)*DELTIM+.5*DDYEND(I)*DELTIM
      DO 400 I=2,NN
      TDELY(I)=TDELY(I)+DELY(I)
  400 TDELX(I)=TDELX(I)+DELX(I)
   41 CALL DEFORM
      CALL EXCITE
      DO 401 I=2,NN
      TDELY(I)=TDELY(I)-DELY(I)
  401 TDELX(I)=TDELX(I)-DELX(I)
      GO TO 45
   42 KOUNT=KOUNT+1
      DO 402 I=2,NN
      TDELY(I)=TDELY(I)+DELY(I)
```

```
      TDELX(I)=TDELX(I)+DELX(I)
      X(I)=X(I)+DELX(I)
  402 Y(I)=Y(I)+DELY(I)
      IF ( NPRINT-KOUNT ) 43,43,46
   43 WOT 6,120, TIME
      WOT 6,121
      WOT 6,124
      DO 50 I=2,NN
   50 WOT 6,122,I,X(I),Y(I),TDELX(I),TDELY(I),DXEND(I),DYEND(I),DDXEND(I
     1),DDYEND(I)
      KOUNT=0
      WOT 6,126
      WOT 6, 123
      WOT 6,125
      DO 51 I=1,NN
   51 WOT6,122,I,FORCB(I),VB(I),BMOMJ(I),COUNTB(I),BCOUNT
   46 IF ( BCOUNT-4. ) 310,44,44
  310 DELTIM=DELTIM*2.
   44 CONTINUE
      DO 75 I=2,NN
  600 PX(I)=X(I)
      PY(I)=Y(I)
      DX(I)=DXEND(I)
      DDX(I)=DDXEND(I)
      DY(I)=DYEND(I)
      DDY(I)=DDYEND(I)
      DELX(I)=DX(I)*DELTIM+(.5-B)*DDX(I)*(DELTIM**2.)+B*DDXEND(I)*(DELTI
     1M**2.)
      DELY(I)=DY(I)*DELTIM+(.5-B)*DDY(I)*(DELTIM**2.)+B*DDYEND(I)*(DELTI
     1M**2.)
      DXEND(I)=DX(I)+.5*DDX(I)*DELTIM+.5*DDXEND(I)*DELTIM
      DYEND(I)=DY(I)+.5*DDY(I)*DELTIM+.5*DDYEND(I)*DELTIM
      TDELY(I)=TDELY(I)+DELY(I)
      TDELX(I)=TDELX(I)+DELX(I)
   75 CONTINUE
      CALL YIELD
      CALL CHECK
      RETURN
      END
```

c. Subroutine CHECK

```
      DIMENSION AND COMMON STATEMENTS ON FIRST PAGE OF
      COMPUTER PRINT-OUT ARE TO BE ADDED HERE.

      SUBROUTINE CHECK
      YCOUNT  = 0.
      DO 13 I=1,NN
      LC(I)=0
      DO 10 II=1,NFIBRE
      IF ( TFEPSB(I,II) ) 11,10,10
   11 IF ( TFEPSB(I,II) + CEPSU ) 12,12,10
   12 YCOUNT=YCOUNT+1.
      LC(I)=-1
      GO TO 13
   10 CONTINUE
   13 CONTINUE
      DO 23 I=2,NN
      JC(I)=0
      DO 20 II=1,NFIBRE
      IF ( TFEPSJ(I,II) ) 21,20,20
   21 IF ( TFEPSJ(I,II)+CEPSU ) 22,22,20
   22 YCOUNT=YCOUNT+1.
      JC(I)=-1
      GO TO 23
   20 CONTINUE
   23 CONTINUE
      DO 31 I=1,NN
      YC=0.
      EPSNEG=0.
      LY(I)=0
      DO 38 II=1,NFIBRE
      IF ( TFEPSB(I,II) ) 39,38,38
   39 EPSNEG=EPSNEG+1.
   38 CONTINUE
      DO 30 II=1,NFIBRE
      IF ( TFEPSB(I,II) ) 32,30,30
   32 IF ( TFEPSB(I,II)+CEPSY ) 33,33,31
   33 YC=YC+1.
      IF ( EPSNEG-YC ) 30,34,30
   34 YCOUNT=YCOUNT+1.
      LY(I)=-1
   30 CONTINUE
   31 CONTINUE
      DO 41 I=2,NN
      YC = 0.
      EPSNEG=0.
      JY(I)=0
      DO48 II=1,NFIBRE
      IF ( TFEPSJ(I,II) ) 49,48,48
   49 EPSNEG=EPSNEG+1.
   48 CONTINUE
      DO 40 II=1,NFIBRE
      IF ( TFEPSJ(I,II) ) 42,40,40
   42 IF ( TFEPSJ(I,II)+CEPSY ) 43,43,41
   43 YC=YC+1.
      IF ( EPSNEG-YC ) 40,88,40
```

```
 88 YCOUNT=YCOUNT+1.
    JY(I)=-1
 40 CONTINUE
 41 CONTINUE
 44 DO 50 I=1,NN
    IF ( LY(I) ) 51,50,50
 51 WOT 6,100,I
 50 CONTINUE
    DO 60 I=2,NN
    IF ( JY(I) ) 61,60,60
 61 WOT 6,101,I
 60 CONTINUE
 45 DO 70 I=1,NN
    IF ( LC(I) ) 71,70,70
 71 WOT 6,102,I
 70 CONTINUE
    DO 80 I=2,NN
    IF ( JC(I) ) 81,80,80
 81 WOT 6,103,I
 80 CONTINUE
    IF ( YCOUNT-2. ) 90,91,91
 91 CALL SYSERR
100 FORMAT (19H YIELD HINGE IN BAR,I3)
101 FORMAT (21H YIELD HINGE AT JOINT,I3)
102 FORMAT (16H CRUSHING IN BAR,I3)
103 FORMAT (18H CRUSHING AT JOINT,I3)
 90 RETURN
    END
```

d. Subroutine DEFORM

```
      DIMENSION AND COMMON STATEMENTS ON FIRST PAGE OF
      COMPUTER PRINT-OUT ARE TO BE ADDED HERE.

      SUBROUTINE DEFORM
      CALL FTRAP
C
      DO 11 I=1,NN
      IF ( ABSF(Y(I+1)-Y(I))-ABSF(X(I+1)-X(I))*687.55 ) 4,3,3
    3 IF ( Y(I+1)-Y(I) ) 5,6,7
    5 ALFA(I)=-1.57080
      GO TO 10
    6 ALFA(I)=0.0
      GO TO 10
    7 ALFA(I)=1.57080
      GO TO 10
    4 ALFA(I)=ATAN((Y(I+1)-Y(I))/(X(I+1)-X(I)))
   10 DBARL(I)=(TDELX(I+1)-TDELX(I))*COS(ALFA(I))+(TDELY(I+1)-TDELY(I))*
     1SIN(ALFA(I))
   11 DALFA(I)=((TDELX(I+1)-TDELX(I))*SIN(ALFA(I))-(TDELY(I+1)-TDELY(I))
     1*COS(ALFA(I)))/(BARL+DBARL(I))
      DO 20 I=1,NN
   20 TEPBAR(I)=DBARL(I)/BARL
      DO 21 I=2,NN
      DANJT(I)=DALFA(I)-DALFA(I-1)
   21 CRVJT(I)=DANJT(I)/BARL
   35 CONTINUE
      CRVJT(1)=0.
      CRVJT(N)=0.
      DO 36 I=1,NN
   36 CRVBAR(I)=(CRVJT(I)+CRVJT(I+1))/2.
      DO 37 I=2,NN
   37 EPSJT(I)=(TEPBAR(I-1)+TEPBAR(I))/2.
      FIBRE=NFIBRE
      DO 40 I=1,NN
      DO 40 II=1,NFIBRE
      XII=II
   40 TFEPSB(I,II)=TEPBAR(I)-(D/2.-(((2.*XII-1.)/2.)*(D/FIBRE)))*CRVBAR(
     1I)
      DO 41 I=2,NN
      DO 41 II=1,NFIBRE
      XII=II
   41 TFEPSJ(I,II)=EPSJT(I)-(D/2.-(((2.*XII-1.)/2.)*(D/FIBRE)))*CRVJT(I)
      DO 42 I=1,NN
      TSEPBT(I)=TEPBAR(I)+DPRIM*CRVBAR(I)
   42 TSEPBB(I)=TEPBAR(I)-DPRIM*CRVBAR(I)
      DO 43 I=2,NN
      TSEPJT(I)=EPSJT(I)+DPRIM*CRVJT(I)
   43 TSEPJB(I)=EPSJT(I)-DPRIM*CRVJT(I)
C
      CALL EXTERN
C
C     STRESS-STRAIN RELATIONSHIPS CONCRETE
      DO 290 I=1,NN
      COUNTB(I)=0.
  400 COUNTB(I)=COUNTB(I)+1.
```

```
      DO 67 II=1,NFIBRE
      YEPSC=CEPSY-PLSETB(I,II)
      IF ( TFEPSB(I,II) ) 59,66,66
   59 IF ( YEPSC-CEPSCR ) 60,60,350
   60 IF ( TFEPSB(I,II)+YEPSC ) 62,62,61
   62 IF ( TFEPSB(I,II)+CEPSCR ) 64,63,63
   64 IF ( TFEPSB(I,II)+CEPSU ) 66,66,65
  350 IF ( YEPSC-CEPSU ) 351,351,358
  351 IF ( TFEPSB(I,II)+YEPSC ) 352,352,355
  352 IF ( TFEPSB(I,II)+CEPSU ) 66,354,354
  355 IF ( TFEPSB(I,II)+CEPSCR ) 356,61,61
  358 IF ( TFEPSB(I,II)+CEPSU ) 66,61,61
   61 FSIGB(I,II)=EC*(TFEPSB(I,II)-PLSETB(I,II))
      GO TO 67
   63 FSIGB(I,II)=-EC*CEPSY
      GO TO 67
   65 FSIGB(I,II)=(-EC*CEPSY)*(1.-(-TFEPSB(I,II)-CEPSCR)/(CEPSO-CEPSCR))
      GO TO 67
   66 FSIGB(I,II)=0.
      GO TO 67
  354 FSIGB(I,II)=(-EC*CEPSY)*(1.-(-TFEPSB(I,II)-CEPSCR)/(CEPSO-CEPSCR))
      GO TO 67
  356 FSIGB(I,II)=EC*(TFEPSB(I,II)-PLSETB(I,II))
      DUMMY=(-EC*CEPSY)*(1.-(-TFEPSB(I,II)-CEPSCR)/(CEPSO-CEPSCR))
      IF ( FSIGB(I,II)-DUMMY ) 357,67,67
  357 FSIGB(I,II)=DUMMY
   67 CONTINUE
C
C     CONCRETE STRESS-FORCE RELATIONS
      CFORCB(I)=0.
      DO 200 II=1,NFIBRE
  200 CFORCB(I)=CFORCB(I)+((D/FIBRE)*FSIGB(I,II))
C
C     TOP REINFORCEMENT IN BARS
      SCRATO=ES/EC
      SEPYPT(I)=SEPSY+SPSTBT(I)
      SEPYPC(I)=-SEPSY+SPSTBT(I)
      ESEPBT(I)=TSEPBT(I)-SPSTBT(I)
  225 IF ( SEPYPC(I) ) 226,232,235
  226 IF ( TSEPBT(I) ) 227,230,231
  227 IF ( TSEPBT(I)-SEPYPC(I) ) 238,238,228
  228 IF ( SEPYPT(I) ) 229,240,240
  229 IF ( TSEPBT(I)-SEPYPT(I) ) 240,239,239
  230 IF ( SEPYPT(I) ) 239,239,240
  231 IF ( SEPYPT(I) ) 239,239,233
  232 IF ( TSEPBT(I) ) 238,238,234
  233 IF ( TSEPBT(I)-SEPYPT(I) ) 240,239,239
  234 IF ( TSEPBT(I)-SEPYPT(I) ) 240,239,239
  235 IF ( TSEPBT(I) ) 238,238,237
  236 IF ( TSEPBT(I)-SEPYPT(I) ) 240,239,239
  237 IF ( TSEPBT(I)-SEPYPC(I) ) 238,238,236
  238 SFORBT(I)=-ES*SEPSY*(SCRATO-1.)*AS/(2.*SCRATO)
      GO TO 241
  239 SFORBT(I)=ES*SEPSY*AS/2.
      GO TO 241
  240 IF ( ESEPBT(I) ) 242,242,243
  242 SFORBT(I)=ES*ESEPBT(I)*(SCRATO-1.)*AS/(2.*SCRATO)
      GO TO 241
  243 SFORBT(I) =ES*ESEPBT(I)*AS/2.
```

```
  241 CONTINUE
C       BOTTOM REINFORCEMENT IN BARS
        SEPYPT(I)=SEPSY+SPSTBB(I)
        SEPYPC(I)=-SEPSY+SPSTBB(I)
        ESEPBB(I)=TSEPBB(I)-SPSTBB(I)
  325 IF ( SEPYPC(I) ) 326,332,335
  326 IF ( TSEPBB(I) ) 327,330,331
  327 IF ( TSEPBB(I)-SEPYPC(I) ) 338,338,328
  328 IF ( SEPYPT(I) ) 329,340,340
  329 IF ( TSEPBB(I)-SEPYPT(I) ) 340,339,339
  330 IF ( SEPYPT(I) ) 339,339,340
  331 IF ( SEPYPT(I) ) 339,339,333
  332 IF ( TSEPBB(I) ) 338,338,334
  333 IF ( TSEPBB(I)-SEPYPT(I) ) 340,339,339
  334 IF ( TSEPBB(I)-SEPYPT(I) ) 340,339,339
  335 IF ( TSEPBB(I) ) 338,338,337
  336 IF ( TSEPBB(I)-SEPYPT(I) ) 340,339,339
  337 IF ( TSEPBB(I)-SEPYPC(I) ) 338,338,336
  338 SFORBB(I)=-ES*SEPSY*(SCRATO-1.)*AS/(2.*SCRATO)
      GO TO 341
  339 SFORBB(I)=ES*SEPSY*AS/2.
      GO TO 341
  340 IF ( ESEPBB(I) ) 342,342,343
  342 SFORBB(I)=ES*ESEPBB(I)*(SCRATO-1.)*AS/(2.*SCRATO)
      GO TO 341
  343 SFORBB(I) =ES*ESEPBB(I)*AS/2.
  341 CONTINUE
C
      FORCB(I)=CFORCB(I)+SFORBT(I)+SFORBB(I)
      IF ( TFEPSB(I,1)*TFEPSB(I,NFIBRE)) 801,801,290
  801 FORDFB(I)=FORCB(I)-EFORCB(I)
      QQ=ABSF(FORDFB(I))
      IF ( QQ-ALERR) 290,290,293
  293 IF ( FORDFB(I)) 294,290,295
  294 DIFEPB(I)=FORDFB(I)/(EC*(D+(SCRATO-1.)*AS))
      GO TO 296
  295 DIFEPB(I)=FORDFB(I)/(ES*AS)
  296 DO 297 II=1,NFIBRE
  297 TFEPSB(I,II)=TFEPSB(I,II)-DIFEPB(I)
      TSEPBT(I)=TSEPBT(I)-DIFEPB(I)
      TSEPBB(I)=TSEPBB(I)-DIFEPB(I)
      GO TO 400
  290 CONTINUE
C
C
      DO 291 I=2,NN
      COUNTB(I)=0.
  450 COUNTB(I)=COUNTB(I)+1.
      DO 87 II=1,NFIBRE
      YEPSC=CEPSY-PLSETJ(I,II)
      IF ( TFEPSJ(I,II) ) 79,86,86
   79 IF ( YEPSC-CEPSCR ) 80,80,370
   80 IF ( TFEPSJ(I,II)+YEPSC ) 82,82,81
   82 IF ( TFEPSJ(I,II)+CEPSCR ) 84,83,83
   84 IF ( TFEPSJ(I,II)+CEPSU ) 86,86,85
  370 IF ( YEPSC-CEPSU ) 371,371,378
  371 IF ( TFEPSJ(I,II)+YEPSC ) 372,372,375
  372 IF ( TFEPSJ(I,II)+CEPSU ) 86,374,374
  375 IF ( TFEPSJ(I,II)+CEPSCR ) 376,81,81
```

```
  378 IF ( TFEPSJ(I,II)+CEPSU ) 86,81,81
   81 FSIGJ(I,II)=EC*(TFEPSJ(I,II)-PLSETJ(I,II))
      GO TO 87
   83 FSIGJ(I,II)=-EC*CEPSY
      GO TO 87
   85 FSIGJ(I,II)=(-EC*CEPSY)*(1.-(-TFEPSJ(I,II)-CEPSCR)/(CEPSO-CEPSCR))
      GO TO 87
   86 FSIGJ(I,II)=0.
      GO TO 87
  374 FSIGJ(I,II)=(-EC*CEPSY)*(1.-(-TFEPSJ(I,II)-CEPSCR)/(CEPSO-CEPSCR))
      GO TO 87
  376 FSIGJ(I,II)=EC*(TFEPSJ(I,II)-PLSETJ(I,II))
      DUMMY=(-EC*CEPSY)*(1.-(-TFEPSJ(I,II)-CEPSCR)/(CEPSO-CEPSCR))
      IF ( FSIGJ(I,II)-DUMMY ) 377,87,87
  377 FSIGJ(I,II)=DUMMY
   87 CONTINUE
C
      CFORCJ(I)=0.
      CMOMJ(I)=0.
      DO 201 II=1,NFIBRE
      XII=II
      CFORCJ(I)=CFORCJ(I)+((D/FIBRE)*FSIGJ(I,II))
  201 0CMOMJ(I)=CMOMJ(I)+FSIGJ(I,II)*((D/FIBRE)*(D/2.-(((2.*XII-1.)/2.)*(
     1D/FIBRE))))
C
C     TOP STEEL AT JOINTS
      SEPYPT(I)=SEPSY+SPSTJT(I)
      SEPYPC(I)=-SEPSY+SPSTJT(I)
      ESEPJT(I)=TSEPJT(I)-SPSTJT(I)
  425 IF ( SEPYPC(I) ) 426,432,435
  426 IF ( TSEPJT(I) ) 427,430,431
  427 IF ( TSEPJT(I)-SEPYPC(I) ) 438,438,428
  428 IF ( SEPYPT(I) ) 429,440,440
  429 IF ( TSEPJT(I)-SEPYPT(I) ) 440,439,439
  430 IF ( SEPYPT(I) ) 439,439,440
  431 IF ( SEPYPT(I) ) 439,439,433
  432 IF ( TSEPJT(I) ) 438,438,434
  433 IF ( TSEPJT(I)-SEPYPT(I) ) 440,439,4[illegible]
  434 IF ( TSEPJT(I)-SEPYPT(I) ) 440,439,4[illegible]
  435 IF ( TSEPJT(I) ) 438,438,437
  436 IF ( TSEPJT(I)-SEPYPT(I) ) 440,439,439
  437 IF ( TSEPJT(I)-SEPYPC(I) ) 438,438,436
  438 SFORJT(I)=-ES*SEPSY*(SCRATO-1.)*AS/(SCRATO*2.)
      GO TO 441
  439 SFORJT(I)=ES*SEPSY*AS/2.
      GO TO 441
  440 IF ( ESEPJT(I) ) 442,442,443
  442 SFORJT(I)=ES*ESEPJT(I,*(SCRATO-1.)*AS/(2.*SCRATO)
      GO TO 441
  443 SFORJT(I)=ES*ESEPJT(I)*AS/2.
  441 CONTINUE
C     BOTTOM STEEL AT JOINTS
      SEPYPT(I)=SEPSY+SPSTJB(I)
      SEPYPC(I)=-SEPSY+SPSTJB(I)
      ESEPJB(I)=TSEPJB(I)-SPSTJB(I)
  525 IF ( SEPYPC(I) ) 526,532,535
  526 IF ( TSEPJB(I) ) 527,530,531
  527 IF ( TSEPJB(I)-SEPYPC(I) ) 538,538,528
  528 IF ( SEPYPT(I) ) 529,540,540
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```
529 IF ( TSEPJB(I)-SEPYPT(I) ) 540,539,539
530 IF ( SEPYPT(I) ) 539,539,540
531 IF ( SEPYPT(I) ) 539,539,533
532 IF ( TSEPJB(I) ) 538,538,534
533 IF ( TSEPJB(I)-SEPYPT(I) ) 540,539,539
534 IF ( TSEPJB(I)-SEPYPT(I) ) 540,539,539
535 IF ( TSEPJB(I) ) 538,538,537
536 IF ( TSEPJB(I)-SEPYPT(I) ) 540,539,539
537 IF ( TSEPJB(I)-SEPYPC(I) ) 538,538,536
538 SFORJB(I)=-ES*SEPSY*(SCRATO-1.)*AS/(2.*SCRATO)
    GO TO 541
539 SFORJB(I)=ES*SEPSY*AS/2.
    GO TO 541
540 IF ( TSEPJB(I) ) 542,542,543
542 SFORJB(I)=ES*ESEPJB(I)*(SCRATO-1.)*AS/(2.*SCRATO)
    GO TO 541
543 SFORJB(I)=ES*ESEPJB(I)*AS/2.
541 CONTINUE

    FORCJ(I)=CFORCJ(I)+SFORJT(I)+SFORJB(I)
    BMOMJ(I)=CMOMJ(I)+DPRIM*(SFORJB(I)-SFORJT(I))
    IF ( TFEPSJ(I,1)*TFEPSJ(I,NFIBRE)) 800,800,291
800 FORDFJ(I)=FORCJ(I)-EFORCJ(I)
    QQ=ABSF(FORDFJ(I))
    IF ( QQ-ALERR) 291,291,451
451 IF ( FORDFJ(I)) 452,291,453
452 DIFEPJ(I)=FORDFJ(I)/(EC*(D+(SCRATO-1.)*AS))
    GO TO 454
453 DIFEPJ(I)=FORDFJ(I)/(ES*AS)
454 DO 455 II=1,NFIBRE
455 TFEPSJ(I,II)=TFEPSJ(I,II)-DIFEPJ(I)
    TSEPJT(I)=TSEPJT(I)-DIFEPJ(I)
    TSEPJB(I)=TSEPJB(I)-DIFEPJ(I)
    GO TO 450
291 CONTINUE
    DO 292 I=1,NN
    II=I+1
    VB(I)=(1./(BARL+DBARL(I)))*(BMOMJ(II)-BMOMJ(I))
292 CONTINUE

    RETURN
    END
```

B. Subroutine EXCITE

```
      DIMENSION AND COMMON STATEMENTS ON FIRST PAGE OF
      COMPUTER PRINT-OUT ARE TO BE ADDED HERE.

      SUBROUTINE EXCITE
C     CALCULATE PRESSURE AMPLITUDE AT TIME T=T
      DO 600 I=2,NN
      IF ( T(I)-TR1 ) 305,305,306
  305 BLAST=(T(I)/TR1)*A1
      GO TO 314
  306 IF ( T(I)-TAR2 ) 307,307,310
  307 IF ( TR2-TAR2 ) 308,309,308
  308 BLAST=A1
      GO TO 314
  309 BLAST=A1+((A2-A1)/(TAR2-TR1))*(T(I)-TR1)
      GO TO 314
  310 IF ( T(I)-TR2 ) 311,313,313
  311 IF ( TR2-TAR2 ) 312,313,312
  312 BLAST=A1+((T(I)-TAR2)/(TR2-TAR2))*(A2-A1)
      GO TO 314
  313 BLAST=A2
  314 CONTINUE
      II=I-1
C     CHECK TO DETERMINE THE PRESENCE OF SPRING 1 AND/OR SPRING 2
      YY=0.
      VV=0.
      ZZ=0.
      IJ=I+1
      IF ( X(I)-X(II) ) 406,407,408
  406 ZX=-1.
      GO TO 409
  407 X(I)=X(I)+.01
      ZX=1.
      ZZ=1.
      GO TO 409
  408 ZX=1.
  409 CHKY1(I)=Y(I)-((Y(I)-Y(II))/(X(I)-X(II)))*ZX
      IF ( ZZ ) 411,411,410
  410 X(I)=X(I)-.01
      ZZ=0.
  411 IF ( X(IJ)-X(I) ) 412,413,414
  412 ZX=-1.
      GO TO 415
  413 X(IJ)=X(IJ)+.01
      ZX=1.
      ZZ=1.
      GO TO 415
  414 ZX=1.
  415 CONTINUE
      CHKY2(I)=Y(I)+((Y(IJ)-Y(I))/(X(IJ)-X(I)))*ZX
      IF ( ZZ ) 417,417,416
  416 X(IJ)=X(IJ)-.01
      ZZ=0.
  417 IF ( Y(I)-CHKY1(I) ) 400,400,401
  400 FX1(I)=0.
      BLAST1(I)=0.
```

```
      YY=1.
401   DEFX2(I)=-TDELX(I)
      IF ( ABSF(DEFX2(I))-.0001 ) 434,402,402
434   DEFX2(I)=0.
402   IF ( Y(I)-CHKY2(I) ) 403,403,404
403   FX2(I)=0.
      BLAST2(I)=0.
      VV=1.
404   DEFX1(I)=TDELX(I)
405   DEFY(I)=-TDELY(I)
      IF ( ABSF(DEFX1(I))-.0001 ) 430,431,431
430   DEFX1(I)=0.
431   IF ( ABSF(DEFY(I))-.0001 ) 432,433,433
432   DEFY(I)=0.
433   IF ( YY ) 365,365,366
365   IF ( DEFX1(I) ) 212,213,213
212   FX1(I)=(FORCY(I)/DEFYY(I))*DEFX1(I)
      GO TO 224
213   FX1(I)=0.
224   BLAST1(I)=RATIO*BLAST*(ABSF(.5*BARL*SIN(ALFA(II)))+ABSF(.5*BARL*SI
     1N(ALFA(I))))
366   CONTINUE
      IF ( VV ) 465,465,466
465   IF ( DEFX2(I) ) 318,319,319
318   FX2(I)=(FORCY(I)/DEFYY(I))*DEFX2(I)
      GO TO 324
319   FX2(I)=0.
324   BLAST2(I)=-RATIO*BLAST*(ABSF(.5*BARL*SIN(ALFA(II)))+ABSF(.5*BARL*S
     1IN(ALFA(I))))
466   CONTINUE
      IF ( DEFY(I) ) 418,419,419
418   FY(I)=(FORCY(I)/DEFYY(I))*DEFY(I)
      GO TO 424
419   FY(I)=0.
424   BLASTY(I)=-BLAST*(ABSF(.5*BARL*COS(ALFA(II)))+ABSF(.5*BARL*COS(ALF
     1A(I))))
566   CONTINUE
      FX1(I)=FX1(I)*(ABSF(.5*BARL*SIN(ALFA(II)))+ABSF(.5*BARL*SIN(ALFA(I
     1))))
      FX2(I)=FX2(I)*(ABSF(.5*BARL*SIN(ALFA(II)))+ABSF(.5*BARL*SIN(ALFA(I
     1))))
      FY(I)=FY(I)*(ABSF(.5*BARL*COS(ALFA(II)))+ABSF(.5*BARL*COS(ALFA(I))
     1))
400   CONTINUE
      RETURN
      END
```

f. Subroutine EXTERN

```
      DIMENSION AND COMMON STATEMENTS ON FIRST PAGE OF
      COMPUTER PRINT-OUT ARE TO BE ADDED HERE.

      SUBROUTINE EXTERN
      DO 67 I=1,NN
      EYEPSC=CEPSY-EPSETB(I)
      IF ( TEPBAR(I) ) 59,66,66
   59 IF ( EYEPSC-CEPSCR ) 60,60,350
   60 IF ( TEPBAR(I)+EYEPSC ) 62,62,61
   62 IF ( TEPBAR(I)+CEPSCR ) 64,63,63
   64 IF ( TEPBAR(I)+CEPSU ) 66,66,65
  350 IF ( EYEPSC-CEPSU ) 351,351,358
  351 IF ( TEPBAR(I)+EYEPSC ) 352,352,355
  352 IF ( TEPBAR(I)+CEPSU ) 66,354,354
  355 IF ( TEPBAR(I)+CEPSCR ) 356,61,61
  358 IF ( TEPBAR(I)+CEPSU ) 66,61,61
   61 EFORCB(I)=EC*(TEPBAR(I)-EPSETB(I))*D
      GO TO 67
   63 EFORCB(I)=-EC*CEPSY*D
      GO TO 67
   65 EFORCB(I)=(-EC*CEPSY)*(1.-(-TEPBAR(I)-CEPSCR)/(CEPSO-CEPSCR))*D
      GO TO 67
   66 EFORCB(I)=0.
      GO TO 67
  354 EFORCB(I)=(-EC*CEPSY)*(1.-(-TEPBAR(I)-CEPSCR)/(CEPSO-CEPSCR))*D
      GO TO 67
  356 EFORCB(I)=EC*(TEPBAR(I)-EPSETB(I))*D
      DUMMY=(-EC*CEPSY)*(1.-(-TEPBAR(I)-CEPSCR)/(CEPSO-CEPSCR))*D
      IF ( EFORCB(I)-DUMMY ) 357,67,67
  357 EFORCB(I)=DUMMY
   67 CONTINUE
C
C     FORCE-STRAIN RELATIONS FOR CONCRETE AT JOINTS
      DO 76 I=2,NN
   76 TEPJT(I)=.5*TEPBAR(I-1)+.5*TEPBAR(I)
      DO 87 I=2,NN
      EYEPSC=CEPSY-EPSETJ(I)
      IF ( TEPJT(I) ) 79,86,86
   79 IF ( EYEPSC-CEPSCR ) 80,80,370
   80 IF ( TEPJT(I)+EYEPSC ) 82,82,81
   82 IF ( TEPJT(I)+CEPSCR ) 84,83,83
   84 IF ( TEPJT(I)+CEPSU ) 86,86,85
  370 IF ( EYEPSC-CEPSU ) 371,371,378
  371 IF ( TEPJT(I)+EYEPSC ) 372,372,375
  372 IF ( TEPJT(I)+CEPSU ) 86,374,374
  375 IF ( TEPJT(2)+CEPSCR ) 376,81,81
  378 IF ( TEPJT(I)+CEPSU ) 86,81,81
   81 EFORCJ(I)=EC*(TEPJT(I)-EPSETJ(I))*D
      GO TO 87
   83 EFORCJ(I)=-EC*CEPSY*D
      GO TO 87
   85 EFORCJ(I)=(-EC*CEPSY)*(1.-(-TEPJT(I)-CEPSCR)/(CEPSO-CEPSCR))*D
      GO TO 87
   86 EFORCJ(I)=0.
      GO TO 87
```

```
  374 EFORCJ(I)=(-EC*CEPSY)*(1.-(-TEPJT(I)-CEPSCR)/(CEPSO-CEPSCR))*D
      GO TO 87
  376 EFORCJ(I)=EC*(TEPJT(I)-EPSETJ(I))*D
      DUMMY=(-EC*CEPSY)*(1.-(-TEPJT(I)-CEPSCR)/(CEPSO-CEPSCR))*D
      IF ( EFORCJ(I)-DUMMY ) 377,87,87
  377 EFORCJ(I)=DUMMY
   87 CONTINUE
C
C     FORCE-STRAIN RELATIONS FOR STEEL IN BARS
      SCRATO=ES/EC
      DO 222 I=1,NN
      SEPYPT(I)=SEPSY+ESPSTB(I)
      SEPYPC(I)=-SEPSY+ESPSTB(I)
      EESEPB(I)=TEPBAR(I)-ESPSTB(I)
      IF ( SEPYPC(I) ) 226,232,235
  226 IF ( TEPBAR(I) ) 227,230,231
  227 IF ( TEPBAR(I)-SEPYPC(I) ) 238,238,228
  228 IF ( SEPYPT(I) ) 229,240,240
  229 IF ( TEPBAR(I)-SEPYPT(I) ) 240,239,239
  230 IF ( SEPYPT(I) ) 239,239,240
  231 IF ( SEPYPT(I) ) 239,239,233
  232 IF ( TEPBAR(I) ) 238,238,234
  233 IF ( TEPBAR(I)-SEPYPT(I) ) 240,239,239
  234 IF ( TEPBAR(I)-SEPYPT(I) ) 240,239,239
  235 IF ( TEPBAR(I) ) 238,238,237
  236 IF ( TEPBAR(I)-SEPYPT(I) ) 240,239,239
  237 IF ( TEPBAR(I)-SEPYPC(I) ) 238,238,236
  238 EFORSB(I)=-ES*SEPSY*(SCRATO-1.)*AS/SCRATO
      GO TO 241
  239 EFORSB(I)=ES*SEPSY*AS
      GO TO 241
  240 IF ( EESEPB(I) ) 242,242,243
  242 EFORSB(I)=ES*EESEPB(I)*(SCRATO-1.)*AS/SCRATO
      GO TO 241
  243 EFORSB(I)=ES*EESEPB(I)*AS
  241 CONTINUE
  222 CONTINUE
C
C     FORCE-STRAIN RELATIONS FOR STEEL AT JOINTS
      DO 262 I=2,NN
      SEPYPT(I)=SEPSY+ESPSTJ(I)
      SEPYPC(I)=-SEPSY+ESPSTJ(I)
      EESEPJ(I)=TEPJT(I)-ESPSTJ(I)
      IF ( SEPYPC(I) ) 326,332,335
  326 IF ( TEPJT(I) ) 327,330,331
  327 IF ( TEPJT(I)-SEPYPC(I) ) 338,338,328
  328 IF ( SEPYPT(I) ) 329,340,340
  329 IF ( TEPJT(I)-SEPYPT(I) ) 340,339,339
  330 IF ( SEPYPT(I) ) 339,339,340
  331 IF ( SEPYPT(I) ) 339,339,333
  332 IF ( TEPJT(I) ) 338,338,334
  333 IF ( TEPJT(I)-SEPYPT(I) ) 340,339,339
  334 IF ( TEPJT(I)-SEPYPT(I) ) 340,339,339
  335 IF ( TEPJT(I) ) 338,338,337
  336 IF ( TEPJT(I)-SEPYPT(I) ) 340,339,339
  337 IF ( TEPJT(I)-SEPYPC(I) ) 338,338,336
  338 EFORSJ(I)=-ES*SEPSY*(SCRATO-1.)*AS/SCRATO
      GO TO 341
  339 EFORSJ(I)=ES*SEPSY*AS
```

```
      GO TO 341
  340 IF ( EESEPJ(I) ) 342,342,343
  342 EFORSJ(I)=ES*EESEPJ(I)*(SCRATO-1.)*AS/SCRATO
      GO TO 341
  343 EFORSJ(I)=ES*EESEPJ(I)*AS
  341 CONTINUE
  262 CONTINUE
C
C     SUMMATION OF THRUSTS IN BARS AND JOINTS
      DO 300 I=1,NN
  300 EFORCB(I)=EFORCB(I)+EFORSB(I)
      DO 301 I=2,NN
  301 EFORCJ(I)=EFORCJ(I)+EFORSJ(I)
      RETURN
      END
```

m. Subroutine INIT

```
      DIMENSION AND COMMON STATEMENTS ON FIRST PAGE OF
      COMPUTER PRINT-OUT ARE TO BE ADDED HERE.

      SUBROUTINE INIT
      DO 76 I=1,NN
      TEPBAR(I)=0.
      PBARL(I)=BARL
      SPSTBT(I)=0.
      SPSTBB(I)=0.
      TSEPBT(I)=0.
      TSEPBB(I)=0.
      EPSETB(I)=0.
      ESPSTB(I)=0.
      DO 76 II=1,NFIBRE
      TFEPSB(I,II)=0.
      PLSETB(I,II)=0.
   76 CONTINUE
      DO 78 I=1,N
      TSEPJT(I)=0.
      TSEPJB(I)=0.
      SPSTJT(I)=0.
      SPSTJB(I)=0.
      DANJT(I)=0.
      BMOMJ(I)=0.
      DO 78 II=1,NFIBRE
      TFEPSJ(I,II)=0.
      PLSETJ(I,II)=0.
   78 CONTINUE
      CC=0.
      TIME=0.
      KOUNT=NPRINT
      Q=0.
      DO 6 I=2,NN
      DELX(I)=0.
      DELY(I)=0.
      TDELX(I)=0.
      TDELY(I)=0.
      EPSETJ(I)=0.
      ESPSTJ(I)=0.
      DDXEND(I)=0.
      DDYEND(I)=0.
      DXEND(I)=0.
      DYEND(I)=0.
      PDDX(I)=0.
      PDDY(I)=0.
      BLAST1(I)=0.
      BLAST2(I)=0.
      BLASTY(I)=0.
      FX1(I)=0.
      FX2(I)=0.
      FY(I)=0.
      DDX(I)=0.
      DDY(I)=0.
      DX(I)=0.
    6 DY(I)=0.
```

```
RETURN
END
```

h. Subroutine LOCATE - Vertical Version

```
      DIMENSION AND COMMON STATEMENTS ON FIRST PAGE OF
      COMPUTER PRINT-OUT ARE TO BE ADDED HERE.

      SUBROUTINE LOCATE
      IF ( Q) 305,305,310
  305 J=1
      DO 300 I=2,N
      IF ( Y(J)-Y(I)) 299,299,300
  299 J=I
C     WAVE FRONT AT J
  300 CONTINUE
      DO 304 I=1,N
  304 WFRTX(I)=Y(J)
C     LOCATION OF WAVE FRONT AT TIMET+DELTA T
  310 TIME=TIME+DELTIM
      DO 308 I=1,N
      WFRTX(I)=WFRTX(I)-SIZVEL*DELTIM
      XDIFFX(I)=Y(I)-WFRTX(I)
      IF ( XDIFFX(I) ) 306,306,307
  306 T(I)=0.
      GO TO 308
  307 T(I)=XDIFFX(I)/SIZVEL
  308 CONTINUE
      RETURN
      END
```

1. Subroutine LOCATE - Horizontal Version

```
 DIMENSION AND COMMON STATEMENTS ON FIRST PAGE OF
COMPUTER PRINT-OUT ARE TO BE ADDED HERE.

      SUBROUTINE LOCATE
      IF ( Q ) 305,305,310
  305 J=1
      DO 300 I=2,N
      IF ( Y(J)-Y(I) ) 299,299,300
  299 J=I
  300 CONTINUE
      PHEE=PHEE*.01745
      DO 301 I=1,N
      WFRTX(I)=-10000000.0+Y(I)*1./(SIN(PHEE)/COS(PHEE))
  301 XDIFFX(I)=ABSF(X(I)-WFRTX(I))
      II=1
      DO 303 I=2,J
      IF ( XDIFFX(I)-XDIFFX(II) ) 302,302,303
  302 II=I
  303 CONTINUE
      Q=1.
C     WAVE FRONT AT MASS II AT TIME T=0
      DO 304 I=1,N
  304 WFRTX(I)=WFRTX(I)+XDIFFX(II)
C     LOCATION OF WAVE FRONT AT TIME T=0+DELTA T
  310 TIME=TIME +DELTIM
      DO 308 I=1,N
      WFRTX(I)=WFRTX(I)+SIZVEL*DELTIM
      XDIFFX(I)=WFRTX(I)-X(I)
      IF ( XDIFFX(I) ) 306,306,307
  306 T(I)=0.
      GO TO 308
  307 T(I)=XDIFFX(I)/SIZVEL
  308 CONTINUE
      RETURN
      END
```

J. Subroutine YIELD

DIMENSION AND COMMON STATEMENTS ON FIRST PAGE OF COMPUTER PRINT-OUT ARE TO BE ADDED HERE.

```
      SUBROUTINE YIELD
      DO 77 I=1,NN
      DO 77 II=1,NFIBRE
      IF ( TFEPSB(I,II)+CEPSY ) 68,68,77
   68 IF ( PLSETB(I,II)-(TFEPSB(I,II)+CEPSY)) 77,77,69
   69 PLSETB(I,II)=TFEPSB(I,II)+CEPSY
   77 CONTINUE
      DO 222 I=1,NN
      R=ABSF(ESEPBT(I))
      IF (R-SEPSY) 222,222,218
  218 IF (ESEPBT(I)) 219,220,221
  219 SPSTBT(I)=TSEPBT(I)+SEPSY
      GO TO 222
  220 SPSTBT(I)=SPSTBT(I)
      GO TO 222
  221 SPSTBT(I)=TSEPBT(I)-SEPSY
  222 CONTINUE
      DO 642 I=1,NN
      R=ABSF(ESEPBB(I))
      IF ( R-SEPSY) 642,642,638
  638 IF ( ESEPBB(I)) 639,640,641
  639 SPSTBB(I) = TSEPBB(I) + SEPSY
      GO TO 642
  640 SPSTBB(I)=SPSTBB(I)
      GO TO 642
  641 SPSTBB(I)=TSEPBB(I)-SEPSY
  642 CONTINUE
      DO 91 I=2,NN
      DO 91 II=1,NFIBRE
      IF ( TFEPSJ(I,II)+CEPSY) 88,88,91
   88 IF ( PLSETJ(I,II)-(TFEPSJ(I,II)+CEPSY)) 91,91,89
   89 PLSETJ(I,II)=TFEPSJ(I,II)+CEPSY
   91 CONTINUE
      DO 262 I=2,NN
      R=ABSF(ESEPJT(I))
      IF ( R-SEPSY) 262,262,258
  258 IF ( ESEPJT(I)) 259,260,261
  259 SPSTJT(I)=SEPSY+TSEPJT(I)
      GO TO 262
  260 SPSTJT(I)=SPSTJT(I)
      GO TO 262
  261 SPSTJT(I)=TSEPJT(I)-SEPSY
  262 CONTINUE
      DO 282 I=2,NN
      R=ABSF(ESEPJB(I))
      IF ( R-SEPSY ) 282,282,278
  278 IF (ESEPJB(I)) 279,280,281
  279 SPSTJB(I)=TSEPJB(I)+SEPSY
      GO TO 282
  280 SPSTJB(I)=SPSTJB(I)
      GO TO 282
  281 SPSTJB(I)=TSEPJB(I)-SEPSY
```

```
282 CONTINUE
    DO 78 I=1,NN
    IF ( TEPBAR(I)+CEPSY) 71,71,78
 71 IF ( EPSETB(I)-(TEPBAR(I)+CEPSY)) 78,78,72
 72 EPSETB(I)=TEPBAR(I)+CEPSY
 78 CONTINUE
    DO 92 I=2,NN
    IF ( TEPJT(I)+CEPSY) 20,20,92
 20 IF ( EPSETJ(I)-(TEPJT(I)+CEPSY)) 92,92,21
 21 EPSETJ(I)=TEPJT(I)+CEPSY
 92 CONTINUE
    DO 232 I=1,NN
    R=ABSF(EESEPB(I))
    IF ( R-SEPSY) 232,232,318
318 IF ( EESEPB(I) ) 319,320,321
319 ESPSTB(I)=TEPBAR(I)+SEPSY
    GO TO 232
320 ESPSTB(I)=ESPSTB(I)
    GO TO 232
321 ESPSTB(I)=TEPBAR(I)-SEPSY
232 CONTINUE
    DO 272 I=2,NN
    R=ABSF(EESEPJ(I))
    IF ( R-SEPSY) 272,272,358
358 IF ( EESEPJ(I) ) 359,360,361
359 ESPSTJ(I)=SEPSY+TEPJT(I)
    GO TO 272
360 ESPSTJ(I)=ESPSTJ(I)
    GO TO 272
361 ESPSTJ(I)=TEPJT(I)-SEPSY
272 CONTINUE
    RETURN
    END
```

2. Summary of FORTRAN Notation Used:

The following is an alphabetic listing of the FORTRAN notation that was used in the preceding computer program.

A1 - a pressure read into the computer to define the pressure-time diagram; see Figure 11

A2 - a pressure read into the computer to define the pressure-time diagram; see Figure 11

ALERB - a constant which when multiplied by the calculated acceleration of a mass gives the allowable difference between the assumed and calculated acceleration of that mass

ALERR - allowable difference between the thrust in a bar or joint calculated by DEFORM and that calculated by EXTERN

ALFA(I) - angle bar I makes with horizontal

AQ - absolute value of the allowable difference between the assumed and calculated acceleration of a mass

AS - total area of reinforcing steel, in^2/in

AX - absolute value of the difference between the calculated and assumed acceleration in the x direction of a mass

AY - absolute value of the difference between the calculated and assumed acceleration in the y direction of a mass

B - Beta, a constant used in the Beta Method

BARL - the original length of the bars, inches

BCOUNT - the number of cycles used in the convergence of the Beta Method

BLAST1(I) - horizontal blast force acting on mass I and exerting force to the right

BLAST2(I) - horizontal blast force acting on mass I and exerting force to the left

BLASTY(I) - vertical blast force acting on mass I and exerting force downward

BLAST - pressure amplitude read from pressure-time diagram stored in computer

BMOMB(I) - total bending moment at the center of bar I

BMOMJ(I) - total bending moment at joint I

CEPSCR - end of the plastic portion of the concrete stress-strain curve; see Figure 8

CEPSO	-	intersection of $\sigma = 0$ and ϵ on concrete stress-strain curve; see Figure 8
CEPSU	-	strain at which concrete crushes; see Figure 8
CEPSY	-	yield strain of concrete; see Figure 8
CFORCB(I)	-	thrust in bar I developed by concrete
CFORCJ(I)	-	thrust in joint I developed by concrete
CHKY1(I)	-	counter to determine if spring 1 in the x direction at mass I is acting
CHKY2(I)	-	counter to determine if spring 2 in the x direction at mass I is acting
CMASS(I)	-	mass concentrated at joint I
CMOMB(I)	-	bending moment at the center of bar I developed by concrete
CMOMJ(I)	-	bending moment at joint I developed by concrete
COUNTB(I)	-	the number of cycles used in the correction of the difference between the thrust in bar I calculated by DEFORM and that calculated by EXTERN
CRVBAR(I)	-	the curvature at the center of bar I
CRVJT(I)	-	the curvature at joint I
D	-	total thickness of structural element, inches
DALFA(I)	-	change in angle which bar I makes with the horizontal
DANJT(I)	-	change in central angle at joint I
DBARL(I)	-	change in the length of bar I
DDXEND(I)	-	acceleration in the x direction of mass I at the end of a time interval
DDX(I)	-	acceleration in the x direction of mass I at the beginning of a time interval
DDY(I)	-	acceleration in the y direction of mass I at the beginning of a time interval
DDYEND(I)	-	acceleration in the y direction of mass I at the end of a time interval
DEFX1(I)	-	deformation of soil spring 1 at mass I
DEFX2(I)	-	deformation of soil spring 2 at mass I

DEFV(I)	-	deformation of the vertical soil spring at mass I
DEFYY(I)	-	yield deformation of the soil springs at mass I, inches
DELTIM	-	time increment
DELX(I)	-	displacement of mass I in x direction
DELY(I)	-	displacement of mass I in y direction
DIFEPB(I)	-	average strain in bar I to correct the difference between thrusts calculated by DEFORM and EXTERN
DIFEPJ(I)	-	average strain in joint I to correct the difference between thrusts calculated by DEFORM and EXTERN
DPRIM	-	distance from the center of the reinforcing steel to the plastic centroid
DUMMY	-	a trial stress computed to determine stress in concrete beyond plastic portion of stress-strain curve
DX(I)	-	velocity of mass I in x direction
DXEND(I)	-	velocity of mass I in x direction at the end of a time interval
DY(I)	-	velocity of mass I in y direction
DYEND(I)	-	velocity of mass I in the y direction at the end of a time interval
E	-	dummy variable used in computer printout
EC	-	concrete modulus of elasticity, psi
EESEPB(I)	-	average "effective" strain in bar I; average strain in bar I minus the plastic set
EESEPJ(I)	-	average "effective" strain in joint I; average strain in joint I minus the plastic set
EFORCB(I)	-	concrete force in bar I computed using average strain for that bar
EFORCJ(I)	-	concrete force in joint I computed using average strain for that joint
EFORSB(I)	-	steel force in bar I computed using average strain for that bar
EFORSJ(I)	-	steel force in joint I computed using average strain for the joint
EPSETB(I)	-	plastic set in bar I arising from the use of average strain for that bar

EPSETJ(I)	- plastic set in joint I arising from the use of average strain for that joint
EPSJT(I)	- average strain at joint I
EPSNEG	- the number of concrete fibers which have a negative strain at time t
ES	- steel modulus of elasticity, psi
ESEPBB(I)	- "effective" strain in the bottom reinforcement of bar I; bottom steel strain minus plastic set
ESEPBT(I)	- "effective" strain in the top reinforcement of bar I; top steel strain minus plastic set
ESEPJB(I)	- "effective" strain in the bottom reinforcement of joint I; bottom steel strain minus plastic set
ESEPJT(I)	- "effective" strain in the top reinforcement of joint I; top steel strain minus plastic set
ESPSTB(I)	- plastic set in steel reinforcement in bar I arising from use of average strain of that bar
ESPSTJ(I)	- plastic set in steel reinforcement in joint I arising from use of average strain of that joint
EYEPSC	- compressive yield strain of concrete using average bar and joint strains; CEPSY minus plastic set
FH1(I)	- horizontal component of thrust in bar I at end nearest joint I
FH2(I)	- horizontal component of thrust in bar I at end nearest joint I +1
FH(I)	- dual notation; horizontal component of thrust in bar I; total horizontal force on joint I
FIBRE	- the number of concrete fibers used to represent the cross-section; limited to a maximum of 20
FORCB(I)	- total force in bar I
FORCJ(I)	- total force in joint I
FORCY(I)	- yield forces in soil springs at mass I, psi
FORDFB(I)	- difference in the thrust in bar I calculated by DEFORM and that calculated by EXTERN
FORDFJ(I)	- difference in the thrust in joint I calculated by DEFORM and that calculated by EXTERN

FSIGB(I,II) - concrete stress in fiber II of bar I

FSIGJ(I,II) - concrete stress in fiber II of joint I

FV1(I) - vertical component of thrust in bar I at end nearest joint I

FV2(I) - vertical component of thrust in bar I at end nearest joint I + 1

FV(I) - dual notation; vertical component of thrust in bar I; total vertical force on joint I

FX1(I) - horizontal force on mass I from soil spring 1

FX2(I) - horizontal force on mass I from soil spring 2

FY(I) - vertical force on mass I from vertical soil spring

GAMMAS - weight of a cubic inch of soil, pci

HGT - a constant which when multiplied by a bar length gives radial distance to which soil is assumed to respond with structure

JC(I) - counter used in the determination of structural collapse

JY(I) - counter used in the determination of structural collapse

KOUNT - a counter to control printout of the computer program

LC(I) - counter used in the determination of structural collapse

LY(I) - counter used in the determination of structural collapse

N - total number of joints in structure; limited to a maximum of 11

NFIBRE - number of fibers used to represent the concrete cross section; limited to a maximum of 20

NN - total number of joints minus one; number of bars in structure

NPRINT - a constant read into computer to control the printout, usually = 2

PALFA(I) - angle bar I makes with the horizontal at the beginning of a time interval, degrees

PDDX(I) - the assumed acceleration of mass I in x direction for any trial iteration in the Beta Method

PDDY(I) - the assumed acceleration of mass I in y direction for any trial iteration in the Beta Method

PHEE - angle wave front makes with the horizontal

PLSETB(I,II) - plastic set in concrete fiber II of bar I

PLSETJ(I,II) - plastic set in concrete fiber II of joint I

PX(I)	- x coordinate of mass I at the beginning of a time interval
PY(I)	- y coordinate of mass I at the beginning of a time interval
Q	- constant used in the location of the wave front
QQ	- absolute difference between thrusts calculated by DEFORM and those calculated by EXTERN
R	- a constant used to determine the time history of strains in concrete and steel
RATIO	- ratio of horizontal to vertical blast pressures on masses; read into machine
SCRATO	- ratio of ES to EC
SEPSY	- yield strain in steel reinforcement
SEPYPC(I)	- compressive yield strain in steel; plastic set minus SEPSY
SEPYPT(I)	- tensile yield strain in steel; plastic set plus SEPSY
SFORBB(I)	- force in the bottom reinforcing steel of bar I
SFORBT(I)	- force in the top reinforcing steel of bar I
SFORJB(I)	- force in the bottom reinforcing steel of joint I
SFORJT(I)	- force in the top reinforcing steel of joint I
SIGY	- dummy variable used in computer printout
SIZVEL	- velocity at which wave traverses the structure, in/sec
SPSTBB(I)	- plastic set in the bottom reinforcing steel of bar I
SPSTBT(I)	- plastic set in the top reinforcing steel of bar I
SPSTJB(I)	- plastic set in the bottom reinforcing steel of joint I
SPSTJT(I)	- plastic set in the top reinforcing steel of joint I
T(I)	- total time the wave has been in contact with mass I; used to determine pressures from a pressure-time diagram
TAR2	- time of arrival of A2; see Figure 11
TDELX(I)	- total displacement of mass I in x direction
TDELY(I)	- total displacement of mass I in y direction
TEPBAR(I)	- total average strain in bar I
TFEPSB(I,II)	- total strain in concrete fiber II of bar I

TFEPSJ(I,II)	-	total strain in concrete fiber II of joint I
TFINAL	-	time at which computer is shut off
TIME	-	total elaspsed time since wave has contacted structure
TR1	-	time required for blast to rise to pressure of A1; see Figure 11
TR2	-	time at which pressure attains an amplitude of A2; see Figure 11
TSEPBB(I)	-	total strain in the bottom reinforcing steel of bar I
TSEPBT(I)	-	total strain in the top reinforcing steel of bar I
TSEPJB(I)	-	total strain in the bottom reinforcing steel of joint I
TSEPJT(I)	-	total strain in the top reinforcing steel of joint I
VB(I)	-	shear at the ends of bar I
VH(I)	-	horizontal component of shear in bar I
VH1(I)	-	horizontal component of shear in bar I at end nearest joint I
VH2(I)	-	horizontal component of shear in bar I at end nearest joint I +1
VV	-	dummy variable to determine the presence of horizontal springs 1 and 2
VV(I)	-	vertical component of shear in bar I
VV1(I)	-	vertical component of shear in bar I at end nearest joint I
VV2(I)	-	vertical component of shear in bar I at end nearest joint I + 1
WFRTX(I)	-	location of wave front with respect to joint I of structure
X(I)	-	x coordinate of mass I at any time
XDIFFX(I)	-	distance between wave front and mass I of structure
XORIG(I)	-	original x coordinate of mass I
Y(I)	-	y coordinate of mass I at any time
YC	-	a constant used in the determination of structural collapse
YCOUNT	-	a constant specifying failure criteria for structure
YEPSC	-	a compressive yield strain of concrete; CEPSY minus plastic set

YORIG(I) - original y coordinate of mass I

YY - dummy variable to determine the presence of horizontal springs 1 and 2

ZX - dummy variable to determine the presence of horizontal springs 1 and 2

ZZ - dummy variable to determine the presence of horizontal springs 1 and 2

3. Summary of Input Data:

The following is a summary, by card number and format, of the basic data input to the computer program. The data are listed by their FORTRAN names, which can be identified by reference to Sub-section 2.

Card No.	FORMAT	VARIABLE NAMES
1	I3,E12.4	N, BARL
2	5E12.4	A1,A2,TR1,TAR2, TR2
3	E12.4	RATIO
4 + a*	5E12.4	FORCY(I) I = 2, N-1
5 + 2a	5E12.4	DEFYY(I) I = 2, N-1
6 + 2a	E12.4	SIZVEL
7 + 2a	2E12.4	DELTIM, TFINAL
8 + 2a	I3,E12.4	NFIBRE,ALERR
9 + 2a	3E12.4	D,DPRIM,AS
10 + 2a	5E12.4	EC,CEPSY,CEPSCR,CEPSU,CEPSO
11 + 2a	2E12.4	ES,SEPSY
12 + 2a + b**	5E12.4	PALFA(I) I = 1, N-1
13 + 2a + b	2E12.4	B,ALERB
14 + 2a + b	E12.4	PHEE
15 + 2a + b	2E12.4	GAMMAS,HGT
16 + 2a + b	I3	NPRINT

* If N-1 > 6 a second card will be required.

** If N-1 > 5 a second card will be required.