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ANL/RAS 89-1

TEMP-STRESS – A Thermomechanical Finite Element Program for the Analysis of Plane and Axisymmetric Reinforced/Prestressed Concrete Structures – User's Manual

by James M. Kennedy,
Phillip A. Pfeiffer, and
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Argonne National Laboratory, Argonne, Illinois 60439
operated by The University of Chicago
for the United States Department of Energy under Contract W-31-109-Eng-38

~~**Applied Technology**~~

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by

James M. Kennedy, Phillip A. Pfeiffer and Algirdas H. Marchertas*

January 1989

~~APPLIED TECHNOLOGY~~

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ABSTRACT

TEMP-STRESS has been developed to improve the understanding of the behavior of concrete subjected to mechanical loadings and high temperatures simulating the effects of coolant spills, molten debris, etc. The capability to model concrete structures subjected to static and dynamic overpressures, such as LWR and LMR containments with complex axisymmetric geometries, can be solved. The computer code is a finite element program which has a weakly coupled thermomechanical formulation. It can handle transient and steady state problems through the use of explicit time integration and dynamic relaxation. There is a plane or axisymmetric continuum element and flexural beam and shell elements for concrete discretization. The continuum element is a four node quadrilateral using numerical integration and elastic hourglass control. Variable material properties as a function of temperature are available. Thermal and/or mechanical loading can be handled. The concrete material model has the following characteristics: a) elastic-plastic response, b) variable loading surface capability, c) cracking normal to maximum principal strain at specified failure surface, d) post-failure element treatment, and e) variable temperature dependence. Concrete can be reinforced and/or prestressed.

1. INTRODUCTION AND OVERVIEW

This report provides the user guidance for a two-dimensional nonlinear finite element computer program for transient and steady-state (dynamic relaxation) analysis of plane and axisymmetric configurations. The program has a capability to study the behavior of concrete structures with a weakly coupled thermomechanical formulation. The finite element method employed is valid for large rotations, large strains and material nonlinearities. A corotational coordinate technique is used (each element being associated with a coordinate system which rotates with that element).

The governing stress equations are solved using an explicit time integration scheme. A conservative stability limitation is imposed on the time-step. Explicit integration is most appropriate for impulsive problems or problems where the loads are of relatively short duration. The explicit scheme is extremely efficient and permits large problems to be solved rapidly. The explicit integration algorithm can also be used in conjunction with dynamic relaxation for steady-state problems. This is advantageous for models where the stiffness matrix is not available or very difficult to program as in the case of the highly nonlinear material behavior of concrete. Dynamic relaxation simulations achieve system equilibrium by iterating until a dual criteria of force and displacement are met. When explicit time integration is performed, lumped masses are used to represent the inertial properties. Slidelines, which are useful for modeling interfaces between materials, such as the liner-concrete interface are an additional feature of explicit time integration. A rigid interface option is included to provide a means of connecting two dissimilar meshes. Energy balance checks and energy partition output can be used to check the fidelity of computations and to assess the distribution of damage and energy absorption in simulations.

An explicit technique is also employed to determine the thermal field in the concrete structure since it is an integral part of the program desired for thermal stress analysis.

The structural finite elements available in the program, except for the thermal elements, are shown in Fig. 1.1 and listed in Table 1.1. These elements are subdivided into two groups:

1. Flexural elements
2. Continuum elements

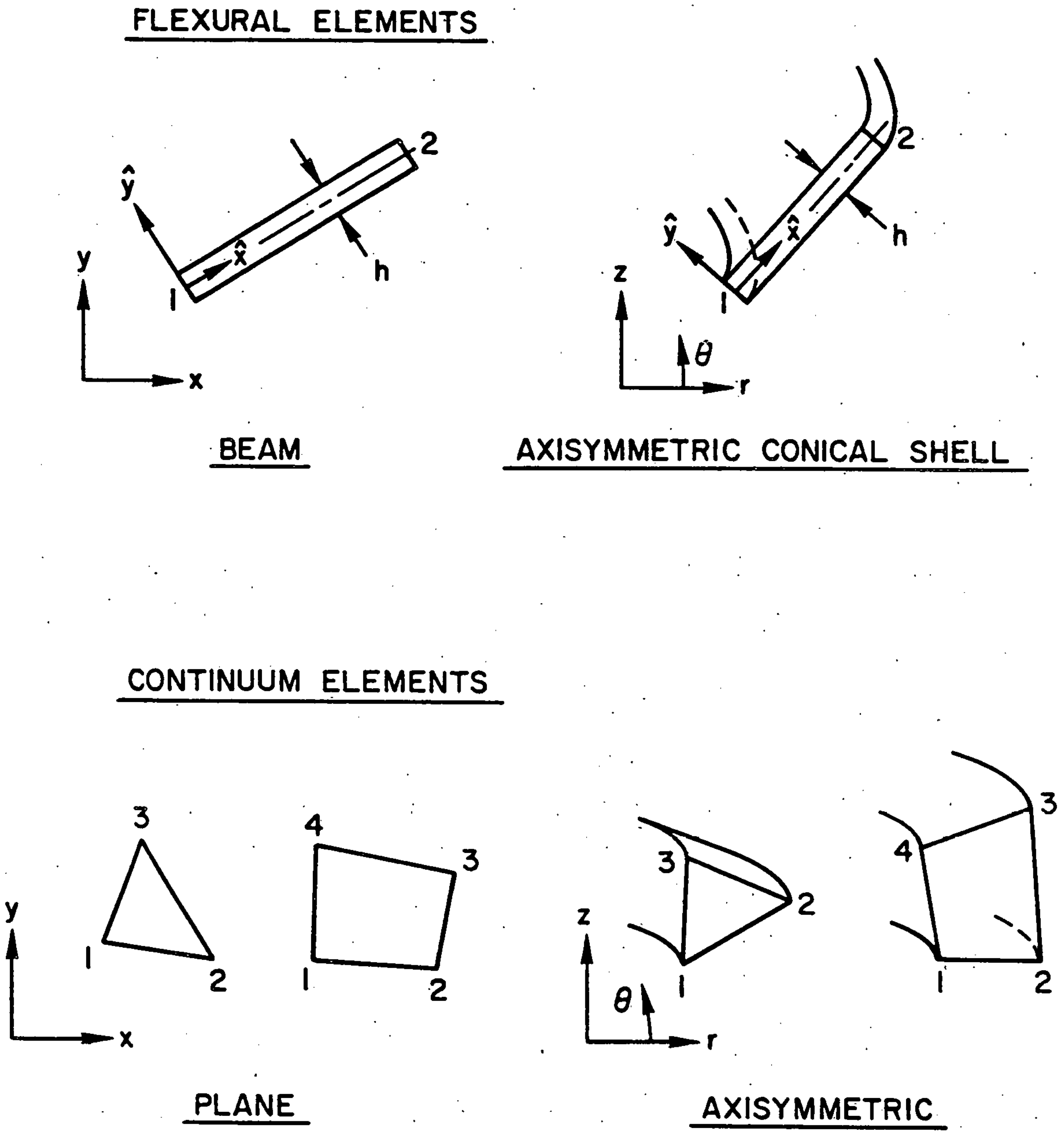


Figure 1.1 Finite Element Library

Table 1.1 Element Library

Flexural Elements

- beam with bar option
- axisymmetric conical shell with membrane and ring options

Continuum Elements

- plane continuum with quadrilateral and triangular* geometry
- axisymmetric continuum with quadrilateral and triangular* geometry

* triangular shape is achieved by collapsing node 4 into node 3

Concrete flexural and continuum elements are the primary elements of the TEMP-STRESS program. Concrete can be reinforced and/or prestressed. Flexural and continuum elements that represent other media are available to facilitate modeling of mixed media configurations. The DYNAPCON program, Marchertas (1982), a forerunner of TEMP-STRESS, had provided the mechanical response of reinforced and/or prestressed concrete structures. The basic element features and architecture of the program are those of the STRAW and WHAMS programs, Kennedy (1974), Belytschko and Mullen (1978) and Kennedy et al. (1985).

The beam and axisymmetric conical shell are the flexural elements used for modeling thin-walled structures. A bar option is available in the beam element while membrane and ring options are available in the shell element for modeling simplifications. Plane and axisymmetric solids can be modeled by use of the continuum elements. The continuum elements are basically quadrilateral in cross-section with triangular shapes achieved by collapsing node 4 into node 3. An arbitrary number of Gauss quadrature points from 1 to n x n can be used in the continuum elements; for one-point quadrature, a consistent hourglass control algorithm is included. In the continuum elements, the coordinate system at each quadrature point is rotated with the material, so arbitrary anisotropic materials can be handled properly when large rotations occur. In the continuum elements, a Jaumann rate is used to maintain proper frame invariance in the material law, but the use of the Jaumann rate limits its application to isotropic materials.

All of these elements (concrete and other media) can be combined in any reasonable manner to model plane two-dimensional problems or axisymmetric three-dimensional problems.

An elastic-plastic law with an associated flow rule is the constitutive relation used for continuum and flexural elements. The non-concrete media employs an isotropic strain hardening material law. The concrete material model includes a mixed isotropic-kinematic strain-hardening formulation, a variable loading surface capability, cracking normal to maximum principal strain at specified failure surface, post-failure treatment, and variable temperature dependence. For the sake of efficiency, options for uniaxial, biaxial or triaxial states of stress or strain within the general subroutine have been developed for use with the flexural and continuum elements. Linear elastic materials can also be handled.

An analysis of the structural integrity of flexural and continuum structures subjected to surface heat fluxes or varying temperature conditions will often involve a thermal stress analysis of the structure. In order to perform either a steady state or transient thermal stress analysis, a thermal analysis must be made for the temperature distribution. Coupled thermomechanical problems can be solved using the flexural and continuum elements. In coupled problems, the thermal response is always transient. However, the stress (mechanical) response can be either transient (dynamic) or quasi-static. A quasi-static response is obtained through the dynamic relaxation technique, and is valid for solutions in which inertial effects are negligible or nonexistent.

The heat conduction (thermal) finite elements are developed to accommodate heat flow through flexural and continuum structural finite elements. To account for thermal stresses arising from temperature variations through the thickness of flexural elements, layered two-dimensional rectangular elements are used. For modeling the temperature variation in the structural continuum elements, quadrilateral thermal elements with a nodal connectivity identical to that of the structure are used. Prescribed temperature, heat flux and film-coefficient (convection) are the thermal boundary conditions available for the thermal field solutions. An internal heat source capability is also available.

Extensive methods are also available for automatically generating mechanical loads. The following load types are available:

a) initial velocities prescribed on nodes
b) pressures applied as functions of time or the volume enclosed by a line of nodes
c) forces applied on nodes

Gravity and special condition (e.g. prestressing) loads can be included if necessary in the simulation.

Displacement boundary conditions which can be treated are quite arbitrary. At any node or any group of nodes, each of the components of displacement in an orthogonal coordinate system may be specified to vanish or have a selected time history.

2. PROGRAM FEATURES

2.1 Elements

2.1.1 Flexural Elements

Two types of flexural elements are included in the program. A plane flexural element which is called a beam element and an axisymmetric flexural element which is used for axisymmetric shell analysis. The cross section of both elements is assumed to be homogeneous and, for the beam, the thickness is assumed to be constant in the entire cross section. The elements are shown in Fig. 1.1. Both elements are initially straight.

In both elements, the in-plane displacements are linear, whereas the transverse displacements are cubic functions of the chord length. The elements are formulated in terms of the usual Bernoulli-Euler hypothesis, so that normals to the midline are constrained to remain straight and normal. In the plane beam element, the strain consequently varies linearly from end to end and linearly across the thickness; in the axisymmetric element the variation is more complex. If the material response is nonlinear, the variation of the stresses through the elements can be quite complex, so that numerical integration is necessary to determine the nodal forces in the element. In the beam element, this integration is accomplished by using the trapezoidal rule through the thickness and along the length, with two points used in the integration along the length. An arbitrary number of integration points through the thickness may be specified by the user. In the axisymmetric element, Gauss integration is used through the thickness with the number of integration points specified by the data; Gauss integration is also used along the chord length (usually two).

The formulation of the flexural elements is based on a modification of the corotational or rigid-convected formulation described by Belytschko and Hsieh (1973). In the present formulation, the strain corresponds to the logarithmic strain in that it is defined by

$$\hat{\varepsilon}_x = \ln \left(\frac{\ell}{\ell_0}\right) \tag{2.1}$$

where ℓ is the current length of the element and ℓ_0 the original length. The stress used in this element corresponds to σ, which is called the physical or Cauchy stress, and is given by

$$\sigma_x = \frac{P}{A} \tag{2.2}$$

where A is the current cross-sectional area and P is the load. The stress-strain data that is input into the program should correspond to this definition of stress and strain. Experience indicates that the program is reasonably accurate for strains of up to 20% for non-concrete media. The exact limits on the magnitudes of strain that can be handled by this element are not clear at this time. Arbitrarily large rotations can be treated.

In the program, the lumped mass matrix is used in conjunction with explicit integration. The lumped mass is quite accurate for problems involving the large displacement, elastic-plastic response of structures.

A flexural element requires three degrees of freedom at each end point: two translational degrees of freedom and one rotation. The program allows for two or three degrees of freedom per node. In order to accommodate the number of degrees of freedom required by a flexural element when using two degrees of freedom per node, a total of four nodes is required for each element. The first two nodes are used for the translational degrees of freedom at the end points. Rotations at each of the end points are associated with two additional nodes called dummy nodes. For each of the dummy nodes, the second degree of freedom is not used at all. Therefore, in the data for flexural elements, one can conceptually treat them as quadrilaterals with two nodes at each end. If several beam elements are connected in a row, both nodes of adjacent elements must be shared in order to assure compatibility of displacements and rotation across the cross section. The use of the dummy node concept enables pin connections to be arbitrarily inserted in a beam, for if two adjacent elements do not share the same dummy node, rotational compatibility is not enforced across the interface, so that a pinned connection results at that point. The two degrees of freedom per node option also allows intermixing with the continuum elements.

In the data for the coordinates of the node of the flexural element, the first two nodes should correspond to the location of the middle surface of the beam or shell at the ends of the element. These are the only nodes necessary if using three degrees of freedom per node. If using two degrees of freedom per node, the third node (first dummy node) corresponds in location with the second node, while the fourth node corresponds in location with the first node. No coordinate data is needed for the dummy nodes. Instead, the dummy node coordinates serve as an optional means for the input of the thickness of the beam. This also allows the thickness of the beam to be varied without new material input data. Similarly, any output for the deformed coordinates of the dummy nodes should be interpreted as meaningless.

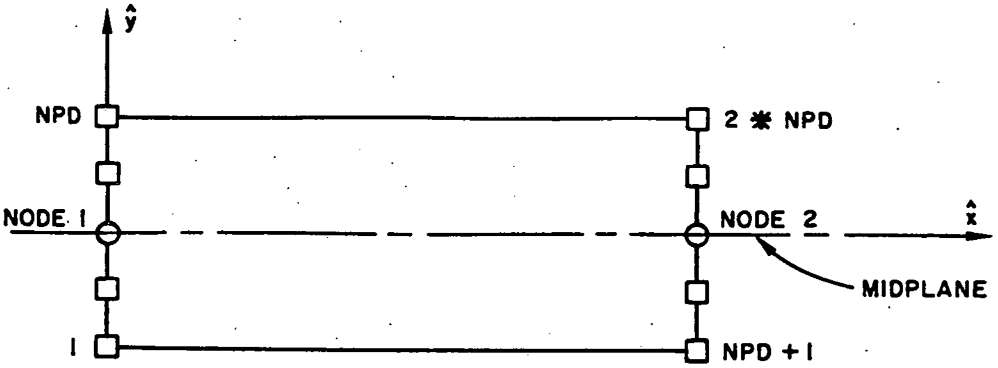
The element data are given for these elements in Section 3. The stations at which stresses and strains can be output depends on the number of integration points specified; if NPD (through the thickness) integration points are specified, each end of the element has NPD stations for a total of NPD x 2. The order of the stations is illustrated in Fig. 2.1; to locate the bottom station of the beam, note that the $\hat{x}$ axis is positive from node 1 to node 2, and the $\hat{y}$ axis is positive counterclockwise from the $\hat{x}$ axis. The bottom station is that with the lowest $\hat{y}$ value.

A special case that is often useful is the bar option of the beam element, in which the bending stiffness is neglected so that the element only has axial stiffness; these elements are often called bars. This option is achieved by simply specifying one integration point through the thickness with two integration points along the length of the element.

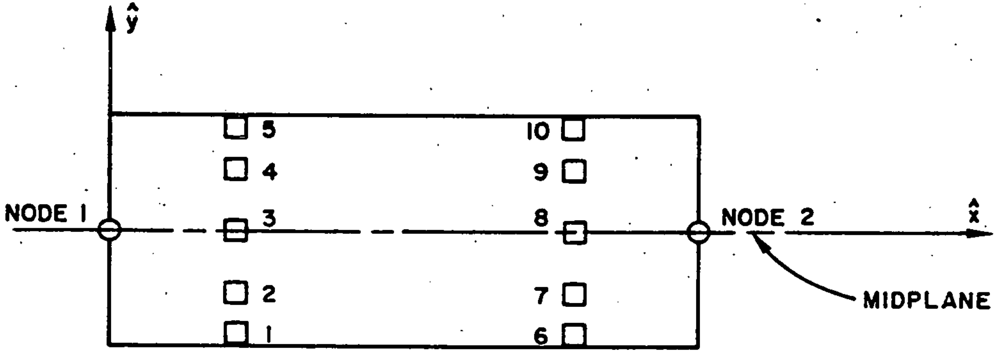
Two special cases of the flexural shell element that are useful in modeling are the membrane and ring options. The membrane option is achieved by specifying one integration point through the thickness and two points along the length. In the membrane option, the flexural stiffness is eliminated so that the element only has resistance to forces tangent to the surface of the shell. Another way of explaining this is to note that in the membrane option, the axial and hoop stresses are constant through the thickness of the shell.

The ring option is obtained by choosing one point integration along the length and through the thickness and making the two nodes coincident by giving them the same node number. As can be seen from Fig. 1.1, when using the ring option, the element becomes a circumferential ring with no bending stiffness.

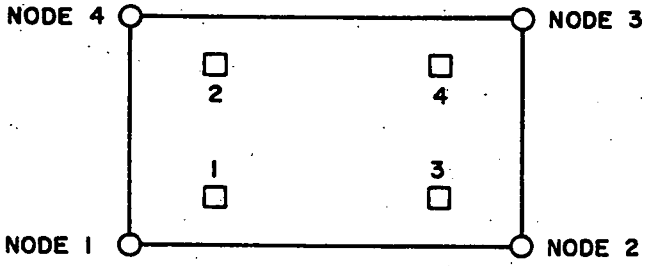
The flexural beam and shell elements that represent concrete media have uniaxial reinforcement that has been superposed on the parent element. The uniaxial reinforcement will be assumed to be embedded parallel to the respective neutral axis/surface of the element. The cross-sectional area, the normal distance of the reinforcement from the neutral axis/surface of the element and the stress-strain data of the reinforcement material are the



BEAM



SHELL - NPD = 5, NPL = 2



CONTINUUM - NGP = 2

Figure 2.1 Location and Numbering of Integration Stations for Flexural and Continuum Elements specified input data. Axial and shear tie are the two types of reinforcement that can be specified at various layers in the beam element; meridional, hoop, helical (seismic) and shear tie are those which can be specified at the various layers in the shell element. Reinforcement options in the shell element are shown in Fig. 2.2. Subscripts refer to various reinforcement layers.

Prestressing is modeled by simple elements, such as rods, rings, and membranes. The rod and the ring elements are used to simulate individual tendons. Specifically, a ring element is utilized for circumferential prestress, and a rod element is used for axial prestress. The axisymmetric membrane (shell without bending resistance) element is used for smearing the prestressing. The membrane element (with Poisson's ratio $\nu = 0$) effectively represents a net of prestress tendons.

The sliding option is used in conjunction with prestressing in order that the tendons can move along prescribed nodes of the concrete analytical model. Sliding along the prescribed sequence of concrete nodes enables the tendons to adjust themselves with respect to the concrete. This sliding feature simulates the actual behavior of the tendons during the prestressing operation and also during the loading of the structure. The prestress load is prescribed by input given in Section 2.6.

2.1.2 Continuum Elements

A linear displacement 4-node quadrilateral with straight sides is the principal element. Triangular elements are achieved by collapsing node 4 into node 3. Plane or axisymmetric geometries can be modeled. A corotational velocity strain-corotational stress formulation is used which is applicable to large strains, large rotations and anisotropic materials.

In the velocity strain formulation, deformation is measured by the velocity strain, which is given in terms of the velocity components v_x, v_y by

$$\begin{aligned} \eta_x &= \frac{\partial v_x}{\partial x} \\ \eta_y &= \frac{\partial v_y}{\partial y} \qquad (2.3) \\ \eta_{xy} &= \frac{1}{2}\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right) \end{aligned}$$

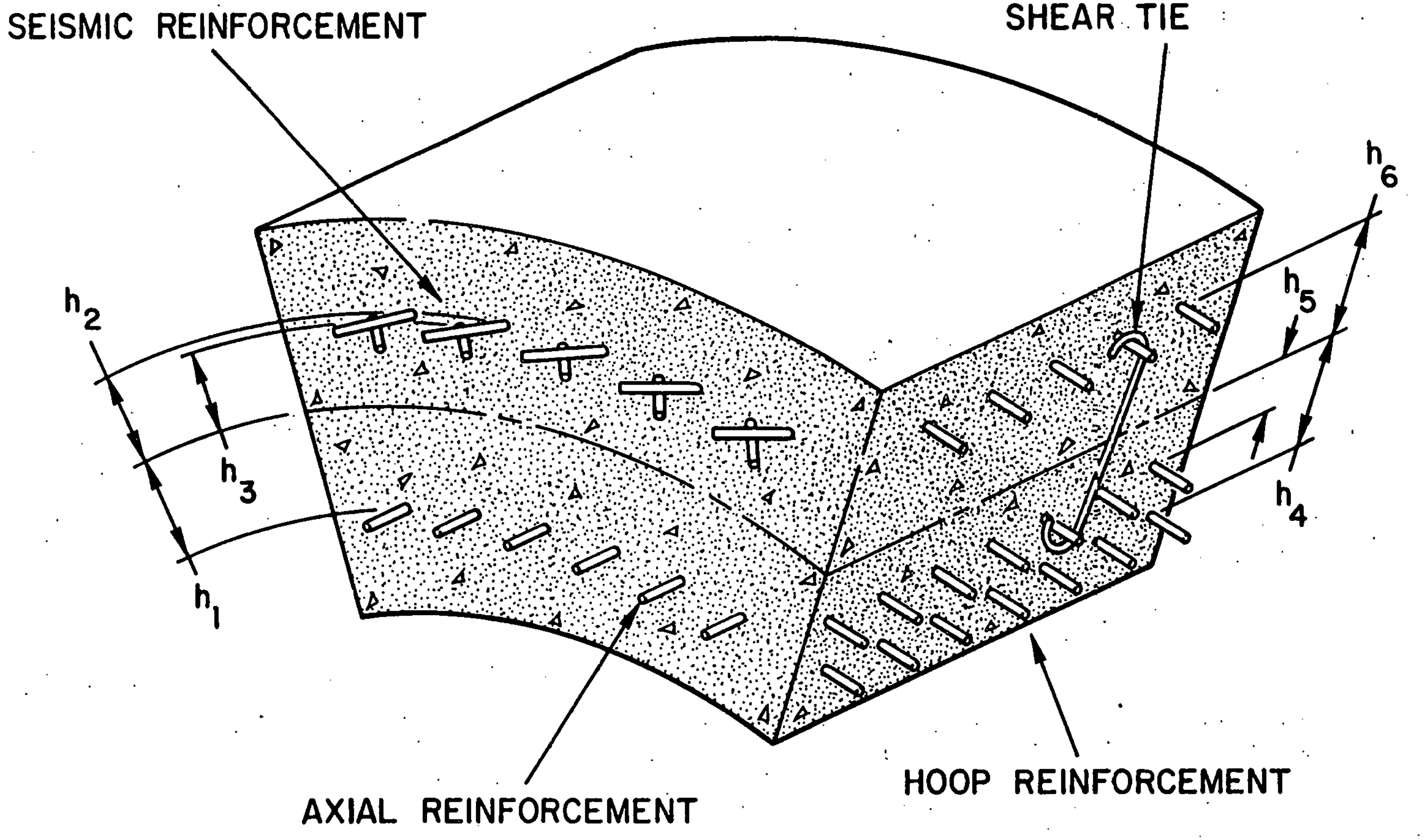


Figure 2.2 Representation of Reinforcement in Concrete of the Axisymmetric Shell Element

Note that the tensor velocity shear strain is stored and used in the program. This strain rate is not integrable, so when the velocity strain formulation is used, the total strain for a general biaxial state of strain has no rigorous meaning. However, in the uniaxial case, the integral of the velocity strain yields the logarithmic strain; thus the stress-strain data for these elements should be given in terms of physical stress versus logarithmic strain.

In the corotational velocity strain formulation, each element is associated with a coordinate system which rotates with the elements $(\hat{x},\hat{y})$. The deformation of the element is then expressed in terms of the velocity strain expressed in the corotational components, viz.

$$
\begin{aligned}
\hat{\eta}_x &= \frac{\partial \hat{v}_x}{\partial \hat{v}} \\
\hat{\eta}_y &= \frac{\partial \hat{v}_y}{\partial \hat{y}} \qquad (2.4) \\
\hat{\eta}_{xy} &= \frac{1}{2}\left(\frac{\partial \hat{v}_x}{\partial \hat{y}} + \frac{\partial \hat{v}_y}{\partial \hat{x}}\right)
\end{aligned}
$$

The stresses are expressed in the same corotational coordinates. Thus the components of the stress tensor are $\hat{\sigma}_x$, $\hat{\sigma}_y$ and $\hat{\sigma}_{xy}$. The alignment of the corotational coordinates relative to the global system (x,y) can be determined at any instant from the angle θ, which is measured counterclockwise from x to $\hat{x}$. The stress-strain law, when expressed in the corotational coordinates, then gives the increment in the corotational stress in terms of the corotational velocity strain in the following form

$$\Delta\hat{\sigma} = f(\hat{\sigma},\hat{\eta}) \qquad (2.5)$$

Since the rate of the corotational stress is frame invariant, no corrections for the rotation are needed. Furthermore, since the constitutive law evaluation is made in the corotational coordinate system, the formulation is applicable to anisotropic materials. Unless otherwise specified, it is assumed that the angle between the corotational coordinate system and the global coordinate system θ is initially zero.

For the continuum elements, the diagonal lumped mass matrix is always used in conjunction with explicit integration.

Figure 2.1 illustrates the number of integration points (two) along one direction for a 4-node quadrilateral element. For this element, 1, 2 and 3 integration points along one direction respectively yield a total of 1, 4 and 9 integration points.

The stations at which element variables can be output correspond to the integration points and are in the order shown in Fig. 2.1. Station 1 is the integration point closest to node 1, and the station numbers are then incremented along the line of integration points parallel to the side defined by nodes 1 and 4. For each station, the order of the variables is the same.

The continuum elements that represent concrete media have reinforcement that is modeled by homogenization; the stress-strain law of the reinforcement is embedded in the stress-strain law of the elements. This approach can account for the direction, the position and the percentage of reinforcement. The reinforcement is assumed to remain rigidly bonded to the concrete; debonding of rebars and concrete is not considered. Reinforcement can be specified in the hoop direction and arbitrary orthogonal directions in the r,z or the x,y plane. The reinforcement arrangement is shown in Fig. 2.3. In addition to that specified within the continuum element, reinforcement can also be modeled by means of discrete rod and ring elements.

2.2 Material Laws

The following elastic-plastic material laws are available for representing non-concrete media:

1. Uniaxial stress for the plane stress beam element.
2. Biaxial stress for plane strain beam, plane stress continuum and axisymmetric shell elements.
3. Triaxial stress for plane strain and axisymmetric continuum elements.

Poisson's ratio should be set to zero when using the bar option of the beam element and the ring option for the shell element.

All of the elastic-plastic laws include isotropic strain hardening, which is isotropic in that the yield value σ_Y in compression and tension grows equally when plastic stresses occur. The current yield value σ_Y for each station is an element variable which may be output.

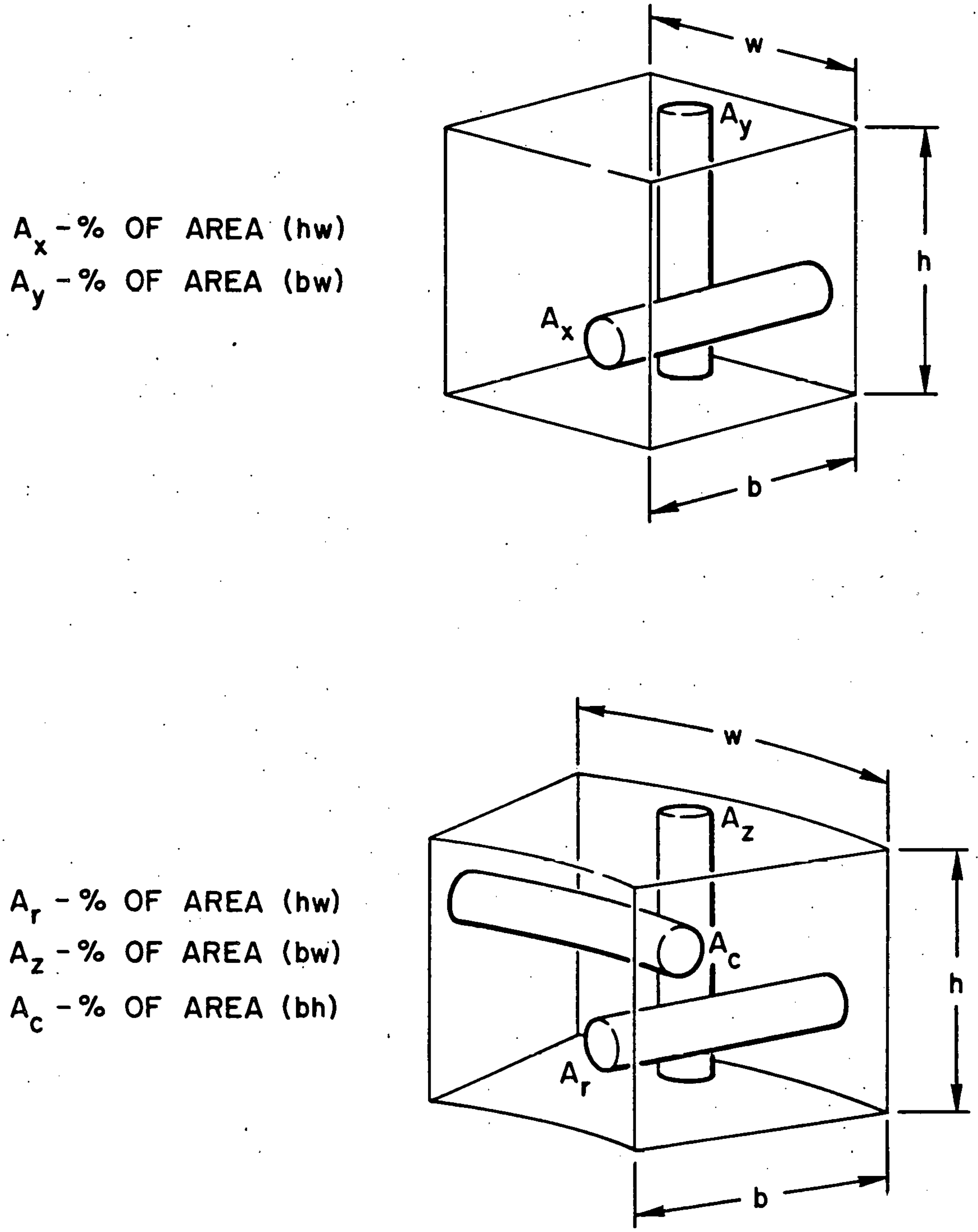


Figure 2.3 Representation of Reinforcement in Concrete for Plane and Axisymmetric Continuum Elements

In the uniaxial law, the stress in the plastic regime is a piecewise linear function of the strain, as shown in Fig. 2.4. The piecewise linear function is described through the points on the stress-strain curve: σ_i and ε_i. The first stress point σ_1 corresponds to the yield stress; the stresses in all subsequent points should be monotonically increasing values. If during the course of the computation the strain exceeds the last strain point which is input, the simulation will terminate with a message indicating the element where the strain was exceeded. The material related element group data for Cards IVb, IVc and IVd are described in Table 2.1.

The biaxial and triaxial laws are based on a Mises yield condition, an associated flow law and isotropic strain hardening; the stress in the plastic regime is a piecewise linear function of the strain, as shown in Fig. 2.4. The input data for these materials is given in Table 2.1. For continuum elements, the strains in the elements are the time integrals of the corresponding velocity strains. Therefore, for large strain problems, these strains are not tensors; however, they are indicative of the magnitudes of the deformation. Whenever a corotational formulation is used, the stress and strain output is in terms of corotational components.

The concrete material law formulation uses a uniaxial relationship for the plane stress beam. A biaxial relationship is used with the plane strain beam, plane stress continuum and axisymmetric shell elements. Finally, a triaxial relationship is used for the plane strain and axisymmetric continuum elements. The material law uses an elastic-plastic stress-strain relationship which includes strain hardening, Takahashi (1983), that can vary from isotropic to kinematic representations, Marchertas et al. (1985). Both associated and non-associated flow rules can be used with either Prager's or Ziegler's formulations. The stress in the plastic regime is a piecewise linear function of strain, as shown in Fig. 2.4. The previous comments about velocity strains and large strains with respect to non-concrete continuum are the same for concrete continuum elements. Two types of constitutive models are available in the code. The difference between the two models is the post-failure response in compression and tension.

In the first constitutive model (preferred) the strength capacity of the concrete in multiaxial stress space is characterized by a four parameter failure surface described by Hsieh, Ting and Chen (1983). The response after

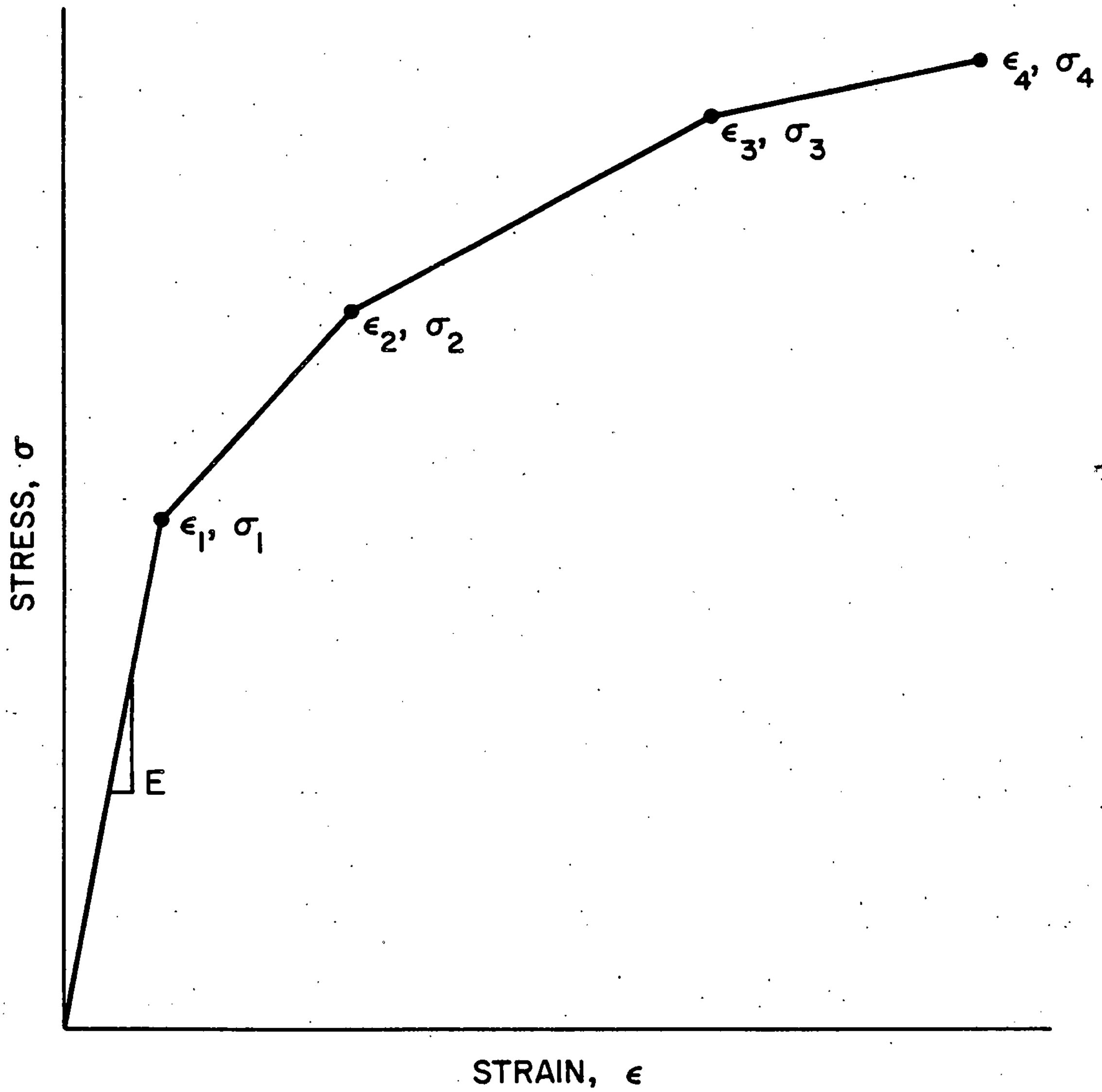


Figure 2.4 Stress-Strain Law for Elastic-Plastic Material

Table 2.1 Summary of Material Data Allocation

LTYP	1	2	3	4	11	12	13	14
element	beam	plane continuum	plane concrete	concrete beam	shell	axi-symmetric continuum	axi-symmetric concrete	concrete shell
Card IVb								
E(1)	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ
E(2)			ν	ν			ν	ν
E(3)	ν	ν	α	α	ν	ν	α	α
E(4)	α	α	α_s	α_s	α	α	α_s	α_s
E(5)	k	k	k	k	k	k	k	k
E(6)	c	c	c	c	c	c	c	c
E(7)	NTP	NTP	NTP	NTP	NTP	NTP	NTP	NTP
E(8)	NSP	NSP	NSP	NSP	NSP	NSP	NSP	NSP
Card IVc								
E(9)	w	t	t	w				
E(10)	h	α_H	α_H	h	h	α_H	α_H	h
E(11)	α_a	α_a	α_a	α_a	α_a	α_a	α_a	α_a
E(12)	$\hat{A}$	$\hat{A}$	RM	RM	$\hat{A}$	$\hat{A}$	RM	RM
E(13)	$\bar{e}_o^i$	$\bar{e}_o^i$	ASC	ASC	$\bar{e}_o^i$	$\bar{e}_o^i$	ASC	ASC
E(14)	ICE	ICE	ICE	ICE	ICE	ICE	ICE	ICE
E(15)	NPL		FSF	FSF	NPL		FSF	FSF
E(16)	NPD	NGP	NGP	NGP	NPD	NGP	NGP	NGP

Table 2.1 Summary of Material Data Allocation (cont.)

LTYP	1	2	3	4	11	12	13	14
element	beam	plane continuum	plane concrete	concrete beam	shell	axi-symmetric continuum	axi-symmetric concrete	concrete shell
Card IVd (repeat for each temperature curve; enter data only to needed pair)								
E(17)	T	T	T	T	T	T	T	T
E(18)	E	E	E	E	E	E	E	E
E(19)	ε_1	ε_1	ε_1	ε_1	ε_1	ε_1	ε_1	ε_1
E(20)	σ_1	σ_1	σ_1	σ_1	σ_1	σ_1	σ_1	σ_1
E(21)	ε_2	ε_2	ε_2	ε_2	ε_2	ε_2	ε_2	ε_2
E(22)	σ_2	σ_2	σ_2	σ_2	σ_2	σ_2	σ_2	σ_2
E(23)	ε_3	ε_3	ε_3	ε_3	ε_3	ε_3	ε_3	ε_3
E(24)	σ_3	σ_3	σ_3	σ_3	σ_3	σ_3	σ_3	σ_3
Card IVe			x	x			x	x
Card IVf			x	x			x	x
Card IVg			x	x			x	x
Card IVh			x	x			x	x
Card IVi			x	x			x	x
Card IVj			x	x			x	x
Card IVk				x				x
Card IVl				x				x

Notation for Table 2.1

ρ : density

ν : Poisson's ratio

α : coefficient of thermal-expansion

k : thermal conductivity

c : specific heat

NTP : number of temperature curves input for this material

NSP : number of stress-strain pairs defining piecewise linear curve

w : beam width

h : beam height and shell thickness

α_a : artificial viscosity

$\hat{A}$: effective strain-rate amplitude parameter

$\bar{e}_o^i$: reference strain-rate

ICE : material law flag

NPL : number of integration points along length

NPD : number of integration points through thickness

t : plane continuum or hydrodynamic element thickness

α_H : hourglass viscosity

NGP : number of Gaussian integration points along one direction

α_s : stress-dependent thermal expansion coefficient

RM : mixed hardening parameter

ASC : flow rule parameter

FSF : failure surface flag

T : temperature

E : Young's modulus

ϵ_i : i-th strain on piecewise linear stress-strain curve, see Fig. 2.4

σ_i : i-th stress on piecewise linear stress-strain curve, see Fig. 2.4

tensile failure is simulated using the element-size-independent cracking criterion established by Bazant and Oh (1983). For tensile failure the cracks are assumed to be normal to the maximum principal strain and are smeared into the element by reducing the stiffness to zero normal to the cracks. Strain softening in the model is available through an energy release term (element size independent feature) or a specified strain at complete failure, which allows the tensile stress normal to the crack to be reduced to zero gradually. For compression failure, the concrete is allowed to crush which essentially sets all the stresses to zero. Strain softening for crushing in the model is also available through an energy release term or a specified strain at complete compression failure. This allows the stresses to be reduced to zero gradually.

The second constitutive model (still under development) is based on an elastic-plastic formulation coupled with the critical state theory used in soils. This has been described by Lin et al. (1987). The elastic-plastic model described earlier is applied up to the maximum strength capacity of material. Beyond this point, the modified critical state theory is used to simulate the material response. In this way, the softening (or hardening) of the material can be taken into account. The softening (or hardening) of the material is facilitated by the shrinkage (or expansion) of a limiting surface in the stress space. This surface is assumed to coincide with the failure surface at the maximum strength of material. It is derived with the help of the five-parameter Willam and Warnke (1974) failure surface. The shape of the limiting surface has the same angular dependence as the failure surface in the deviatoric plane. In the meridian plane, the shape is assumed to be that of a slanted ellipse. It is applicable to concrete, geomaterials, and other materials which have different strengths in tension and compression.

2.3 Time Integration

2.3.1 Dynamic Relaxation

For processes where the stiffness matrix is not available or very difficult to program as in the case of highly nonlinear materials, quasi-steady state and steady state (static) solutions may be attained by dynamic relaxation. Dynamic relaxation is a process in which sufficient damping is added to the system so that through the solution of the equations of motion, the final equilibrium position is reached. Both mass-proportional and stiffness-proportional damping are available. For steady state solutions, only mass-proportional damping is used (90% is recommended).

In the computer program, the external loads are prescribed by input. To facilitate dynamic relaxation, this loading is applied incrementally, i.e., in load steps of specified magnitude. Hence, dynamic relaxation for each of the load increments permits readjustment of the structure while approaching static equilibrium asymptotically, as shown in Fig. 2.5. Static equilibrium is attained at definite points as indicated in Fig. 2.5.

Equilibrium of the system is established by the imposition of two criteria. One of the criterion is equivalent to the comparison of internal forces with the external forces at the same iteration step. The other criterion is tantamount to the comparison of the change of displacements at successive iteration steps.

2.3.2 Stable Time Step

The explicit integration is carried out by the central difference method. The stability properties (structural) of this integration procedure limits the time step by

$$\Delta t \leq \frac{2}{\omega_{max}} \left[(1 + \mu^2)^{1/2} - \mu \right] \tag{2.6}$$

where ω_{max} is the maximum eigenvalue (the highest frequency) of the system and μ is the fraction of critical damping in the highest frequency. The formulas for the stability calculations are summarized in Table 2.2.

The program has provisions for automatically calculating Δt (structurally) for each simulation using Eq. (2.6) with a reduction factor (0.8 to 0.9 of the stable Δt is recommended) to be specified by the user. The user usually should check for conservation of energy in the computation. An energy imbalance greater than a few percent usually indicates that a numerical instability has occurred during the course of the computation. Energy output can be obtained as described on Card Xc.

When the explicit integration technique is applied to solve a transient problem, the time parameter used pertains to the actual time of the physical process. In quasi-steady state and steady state problems the time parameter in explicit integration loses its original meaning; it no longer means real time, but rather an integration parameter proportional to time.

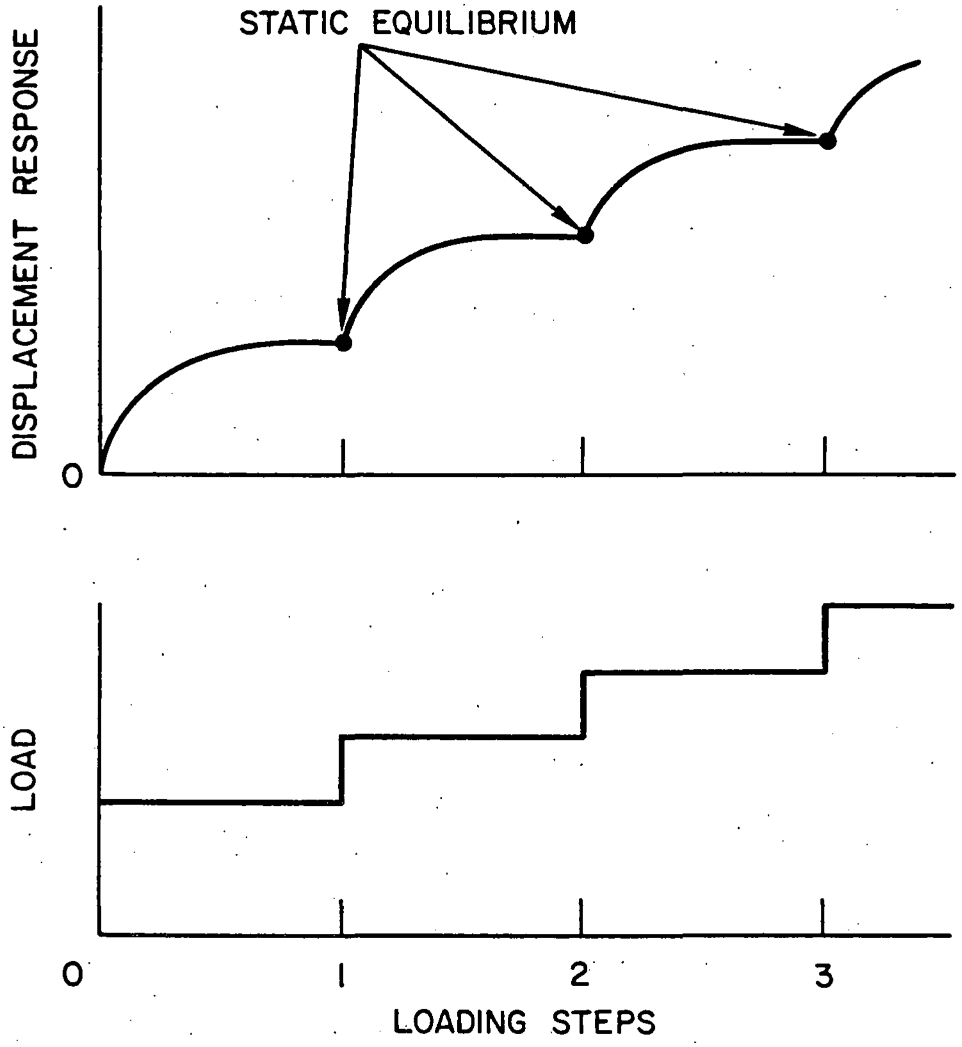


Figure 2.5 Loading Method for Dynamic Relaxation

Table 2.2 Guidelines for Stable Time Step in Explicit Calculations

$$\Delta t \le \frac{2}{\omega_{max}} \left((1 + \mu^2)^{1/2} - \mu \right)$$

<u>Square of Maximum Frequency</u>

beam and shell

$$\omega_{max}^2 = \frac{4c^2}{\ell^2} \quad \text{or} \quad \frac{16c^2h^2}{\ell^4} \quad \text{(whichever is larger)}$$

continuum

$$\omega_{max}^2 = \frac{2c^2}{A^2} \left(\gamma_1 + (\gamma_1^2 - \bar{\nu}\gamma_2)^{1/2} \right)$$

$$\gamma_1 = \frac{1}{2} (y_{24}^2 + y_{31}^2 + x_{42}^2 + x_{13}^2) \qquad \bar{\nu} = \frac{4(1 - 2\nu)}{1 - \nu^2}$$

$$\gamma_2 = \frac{1}{4} (y_{24}^2 + y_{31}^2)(x_{42}^2 + x_{13}^2) - \frac{1}{4} (y_{24}x_{42} + y_{31}x_{13})^2$$

<u>Square of Elastic Wavespeed</u>

beam and shell

$$c^2 = \frac{E}{\rho} \begin{pmatrix} \text{uniaxial} \\ \text{plane} \\ \text{stress} \end{pmatrix} \quad \text{or} \quad \frac{E}{\rho(1 - \nu^2)} \begin{pmatrix} \text{uniaxial} & & \text{biaxial} \\ \text{plane} & \text{or} & \text{plane} \\ \text{stress} & & \text{stress} \end{pmatrix}$$

continuum

$$c^2 = \frac{E}{\rho(1 - \nu^2)} \begin{pmatrix} \text{plane} \\ \text{stress} \end{pmatrix} \quad \text{or} \quad \frac{E(1 - \nu)}{\rho(1 + \nu)(1 - 2\nu)} \begin{pmatrix} \text{plane} \\ \text{strain} \end{pmatrix}$$

Δt = stable time step
ω_{max} = maximum frequency
μ = critical damping fraction
c = elastic wavespeed
ℓ = length of element
h = thickness of beam or shell

A = cross-sectional area
E = Young's modulus
ρ = mass density
ν = Poisson's ratio
x_{ij} = x-coordinate difference
y_{ij} = y-coordinate difference

For purely statics problems this time parameter becomes solely an integration parameter.

From Table 2.2, it can be seen that an inefficient time step (too small) may result if there are large differences in element sizes or large differences between translational and/or rotational frequencies which, for static solutions, will cause excessive computation time. This inefficiency may be overcome by using a concept of mass-adjustment. The principal feature of this method is to use a constant Δt (usually $\Delta t = 1.0$ for convenience). This is done by adjusting the mass density, ρ, for both translational and rotational frequencies, utilizing the stability time limit relationship given in Eq. (2.6). From experience, by utilizing the adjusted mass scheme, a considerable saving in computational time may result, depending on the type of structure and discretization used.

For thermal solutions, the critical time step is

$$\Delta t = \frac{\rho c \ell}{2k} \tag{2.7}$$

where ℓ is the shortest distance between nodes, ρ is the mass density, c is the specific heat, and k is the conductivity.

2.3.3 Artificial Viscosities

In the integration of the finite element equations of motion with small time steps, such as is generally the case in explicit integration, high frequency oscillations which are called "spurious oscillations" or "aliasing" will appear in an undamped system. The severity of these oscillations tends to increase if the mesh is rather heterogeneous. These oscillations can be reduced and sometimes eliminated by the use of a suitable artificial viscosity, which is really a numerical damping.

The program has a provision for including a linear artificial viscosity. For a uniaxial stress-strain law this artificial viscosity is of the form

$$\hat{\sigma}_{vis} = \frac{2\mu E}{\omega_{max}} \hat{\eta} \tag{2.8}$$

where μ is a constant input by the user, E is Young's modulus and ω_{max} is the maximum eigenvalue of the system. For constant strain type elements, which include the continuum elements and the membrane part in the beam element, μ corresponds to the fraction of critical damping in the highest element mode. For most cases, a value of μ between 0.02 and 0.10 is recommended. Note that according to Eq. (2.6) the use of an artificial viscosity reduces the stability limit on the time step.

2.4 Mesh Generation

Nodal coordinates may be a mix of cartesian and polar systems with polar systems permitted to be defined in local coordinates. Some mesh generation features are included. Intermediate node coordinate data can be skipped if:

1. The coordinates can be generated by equispacing these nodes.
2. The coordinates between two nodes can be generated by changing the distance between each sequential pair of nodes by a specified ratio.

The ratio of distances between automatically generated nodes can be specified by using KONTRL(3) on Card III.

Intermediate element node data can be skipped if the elements have the same material type number, MTYP, and are of the same element type, LTYP, and the nodes can be generated by:

1. Adding 1 to the node numbers of the previous element.
2. Adding a number INCR to the node numbers of the previous element.

2.5 Boundary Conditions/Support Conditions

Prescribed displacement boundary conditions/support conditions which can be treated by the program are quite arbitrary. At any node or for any group of nodes, either one or two components of the displacements in an $(\hat{x},\hat{y})$ coordinate system may be specified to vanish or to have a selected time history. The $(\hat{x},\hat{y})$ coordinate system may be aligned arbitrarily in space relative to the global coordinate system, in that case, the angle θ from x to $\hat{x}$, positive in a counter-clockwise sense, has to be input. If no angle θ is input, the $(\hat{x},\hat{y})$ system is assumed to coincide with the global coordinate system. The rotation nodes or component can also have prescribed conditions. Since the formulation is based on a displacement type of finite element method, no conditions need to be prescribed on stress free boundaries.

If displacements are prescribed nonzero values, these values can be arbitrary piecewise linear functions of time, which are input through the load line data, Cards VIII.

2.6 Loading

The program has provisions for several types of loading on the model:

1. Initial values of velocities on a line of nodes specified by the user.
2. Pressure loads applied on a line of nodes where the pressure may be an arbitrary piecewise linear function of time or volume; this function is specified by the data f_i and t_i as shown in Fig. 2.6.
3. Forces, displacements or thermal loads applied on an arbitrary set of nodes, where the forces, displacements thermals may be arbitrary piecewise linear functions of time.
4. Prestressing an arbitrary set of elements; this loading condition is applied prior to the desired simulation.
5. Gravity loading specified by using KONTRL(6) on Card III and the detailed data of acceleration of gravity rate and the direction cosines for the gravity on Card XI.

A load line is here defined as a set of node points; for initial velocity and pressure loadings, the load line must consist of a sequence of adjacent node points (elements). For applied forces and displacements, the load line may be an arbitrary set of nodes. For thermal loads, temperatures are applied to an arbitrary set of nodes (minimum of two) while heat fluxes and film coefficients are applied to a line of nodes (elements). Prestressing and internal heat sources are applied to an arbitrary set of elements. Nodes and elements specified for thermal loads are those of the thermal mesh.

Whenever pressure, initial normal or tangential velocities or heat flux are prescribed, it is necessary that a positive direction be defined for these quantities. This is accomplished as shown in Fig. 2.7. First, a positive direction is defined for the load line as that direction obtained by tracing a line in the order that the nodes are numbered for the load line. The positive normal direction is then obtained by rotating clockwise 90° from the positive load line direction. A positive pressure, positive normal initial velocity or positive heat flux is applied in that direction, whereas a negative pressure, negative normal velocity or negative heat flux is applied opposite to the direction shown. The positive tangential direction corresponds to the direction of the load line.

Load lines are used to input a specified prestress to the tendon elements. In quasi-static problems, prestressing is prescribed by means of

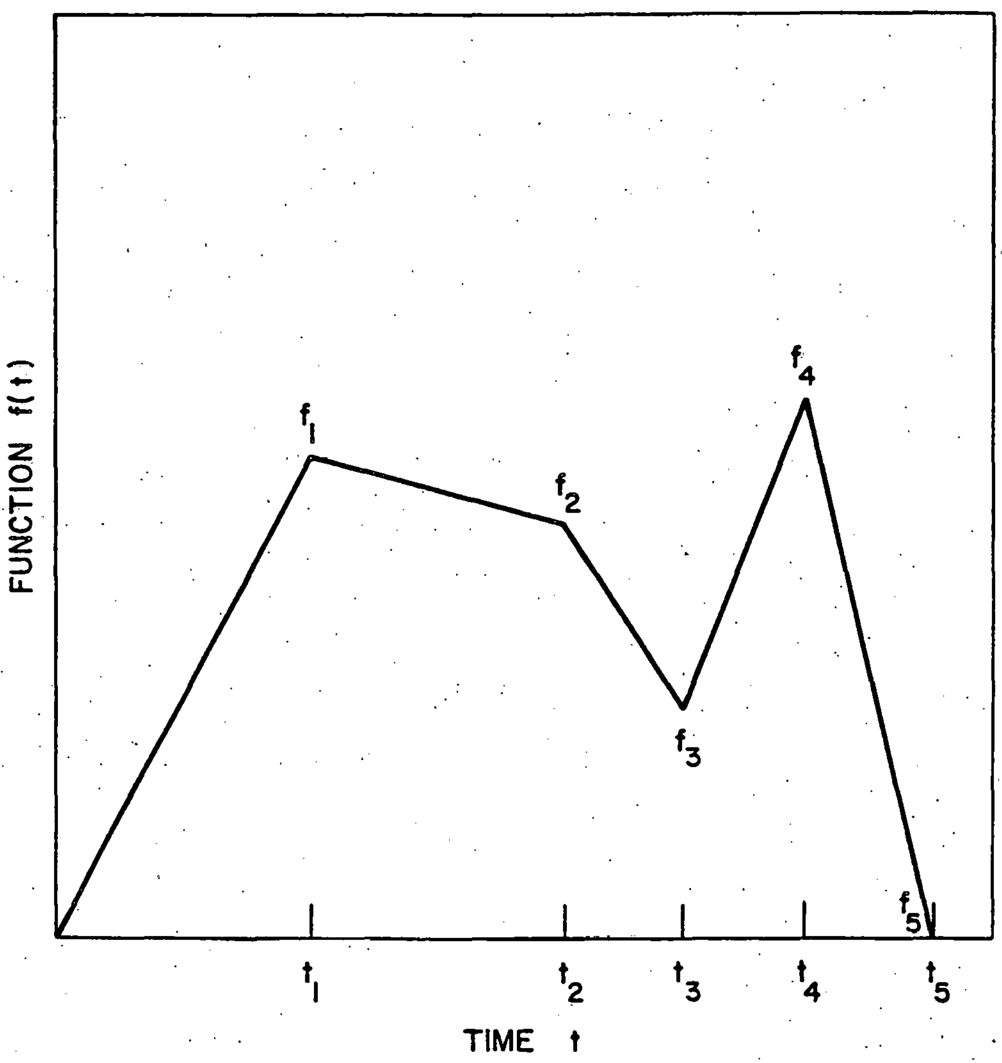
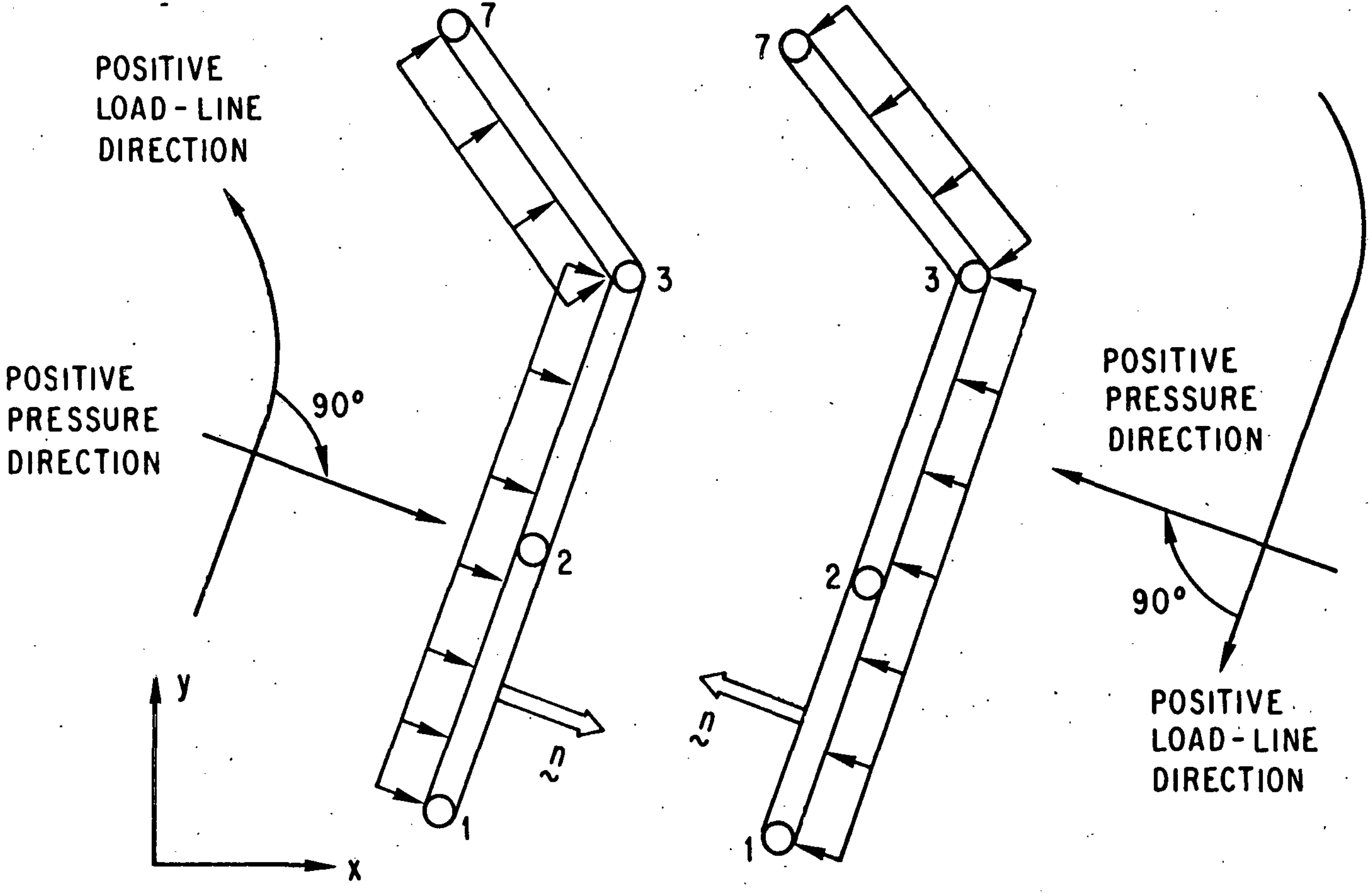


Figure 2.6 Functions $f(t)$ as Defined by f_i and t_i; $f(t)$ may be a Pressure, Nodal Force, Displacement or Thermal



(a) (b)

Figure 2.7 Sign Convention for Load Lines and Applied Loads; in Case (a): the Nodes are Numbered in the Order 1, 2, 3, 7; Case (b): 7, 3, 2, 1 one step load. This is possible because of large structural damping (as much as 90%) associated with the quasi-static type problems. For dynamic problems, prestressing would be specified by a gradual ramp load so as not to generate inertial effects (which could cause premature cracking in the concrete). Prestressing is a preload which precedes the thermal and/or mechanical loading for the simulation. These loadings (prestress load followed by thermo-mechanical) are applied in a sequential manner.

2.7 Sliding Interface

For the purpose of treating interfaces between two solids that are not physically bonded and regions where severe discontinuities in tangential displacements are expected, sliding interfaces have been included. The sliding interfaces may be straight or piecewise linear curves, but sharp corners should be avoided. The model included here cannot treat debonding, so the regions on both sides of the interface must remain in contact. For purposes of modeling tangential forces across the interface, simple Coulomb friction and viscous force models have been included. Only small relative displacements can be handled on the slide line.

2.8 Rigid Interface

The rigid interface option provides a means of connecting two dissimilar meshes. Three types of rigid interfaces are included, one for joining continuum meshes of different size elements, the second for joining continuum elements to flexural elements and the third for connecting multiple sets of flexural elements. These will be called the continuum, flexural and flexural offset interfaces, respectively. While meshes of two different sizes can be interconnected through triangles, the rigid sideline is more convenient because the resulting meshes are more easily generated in an automatic fashion.

In using a rigid continuum interface, one side must be designated as master, the second as slave. The option works best when the side with the more massive nodes, which is usually the side with the larger elements, is chosen to be the master side.

A second application for the rigid interface is for joining flexural elements, such as the beam or axisymmetric shell, to continuum elements, which is called the rigid flexural interface. The rigid interface should be perpendicular to the midline of the flexural element.

In this option, the flexural node should always be the master node. The interaction between the flexural master node and the continuum slave nodes is based on the assumption that the entire slave line remains straight and rotates with the flexural node, i.e., the Kirchhoff assumption is imposed on the continuum nodes.

The rigid interface can also be used to represent two flexural elements that act together and have noncommon midplanes (e.g. lined structures) by letting one set of flexural nodes be the master nodes, the second set be slave nodes. Generally the more massive structure should be assigned to be the master nodes. In using this option, the spacing of the slave nodes and master nodes should be approximately equal. This feature can only be used in the two degree of freedom per node option. The liner may also be a membrane without flexural resistance. Multiple layering of elements can also be handled with multiple sets of rigid interface data that have the same set of master nodes with different sets of slave nodes. Thus sandwich shells may be modeled effectively and efficiently without the penalty of a small stable time step that results when layers are connected with stiff, deformable elements. Only the translational nodes are necessary for nodal input data. The rotational nodes are generated internally for those elements with flexural resistance.

2.9 Output

The program has options for two types of output:

1. Time histories of selected displacement, velocity, and acceleration components, and time histories of selected element variables, such as stresses or strains.
2. At particular time steps either displacements, velocities or accelerations at all nodes and/or element variables in all stations in all elements may be printed.

The time histories may be printed with a frequency specified by the user, and, in addition, they may be plotted with a printer plotter or with DISSPLA. For any time histories which are selected for plotting, the variables at the selected frequency are stored in core, so that the number of time histories selected influences the core storage requirements of the program.

The method for selecting particular displacement, velocity or acceleration components is quite straightforward: the user simply specifies the node number, whether he desires a displacement, velocity or acceleration, and the choice of plotting and/or printout. The selection of element variables for time history output is more complex, for the user must specify the index of the variable he selects in addition to the element number. The indexing procedure for variables depends on the element type, the material type, and the arrangements of the output station, which correspond to the integration points used in the element. Therefore, in order to specify the index, the user must know how the stations are arranged in a particular element, and how the variables are arranged in each station, which depends on the material type.

3. PROGRAM INPUT

3.1 Input Format Overview

The program uses a fixed input format, so all data must be input exactly according to the format specified for each card, and the card groups must appear in sequence according to their number. Some variables, which are commonly considered integers, such as E(7) on Card IVb-1, are input as floating point numbers; they should not be input as integers.

An outline of the data is given in Table 3.1. This table gives the order in which the data appears and when it can be omitted. The details of the data cards are given in the following. Prior to constructing his own data sets, the user is advised to peruse Section 4 which gives data sets for some sample problems.

Table 3.1 Input Data Structure Overview

Card	Description	When Needed
I	Title	for all data sets
II	Parameter	for all data sets
III	Control	for all data sets
IV	Material property	when element appears in mesh
IVa-1 (a to d)	Beam element	
IVa-2 (a to d)	Plane continuum element	
IVa-3 (a to j)	Plane concrete element	
IVa-4 (a to l)	Concrete beam element	
IVa-11 (a to d)	Shell element	
IVa-12 (a to d)	Axisymmetric continuum element	
IVa-13 (a to j)	Axisymmetric concrete element	
IVa-14 (a to l)	Concrete shell element	
V	Node	for all data sets
VI	Element	for all data sets
VII	Prescribed displacement	only if NUMDIS > 0

Table 3.1 Input Data Structure Overview (cont.)

VIIIa	Load line (parameters)	for all data sets
VIIIb-1	Load line (time history)	only if IVOL(1) > 0
VIIIb-2	Load line (initial velocity)	only if IVOL(1) = 0
VIIIc	Load line (nodes/elements)	for all data sets
IXa	Sliding/rigid interface (parameters)	only if NSLID > 0
IXb	Sliding/rigid interface (nodes)	only if NSLID > 0
IXc	Sliding/rigid interface (nodes)	only if NSLID > 0
Xa	Output	for all data sets
Xb	Motion output	only if NPRU > 0
Xc	Element output	only if NPRS > 0
Xd	Picture output	only if NPIC > 0
XI	Gravity loading	only if KONTRL(6) = 1

3.2 Restart Procedure

The user has the option to prescribe a time step number in which data for a restart will be written on Unit 12. In order to use this restart data, it is only necessary to provide the data written on Unit 12 and Cards I and II from the input stream described in the following section. Two modifications to the input are also available during a restart. Include these cards only if changes are to be made. A load line and the time step or load increment for global output may be modified as long as there is no change in the original array dimensioning. Parameters such as the number of nodes on the load line, the number of points defining the loading function and the number of output pictures may not be altered. Nodes, loading function values and picture time steps, however, can be modified. If there are changes, all Cards VIII and Xd must be included; even unmodified load lines. Other modifications to various parameters (e.g., the maximum number of iterations per load increment value on the control card) can be achieved by recompiling appropriate subroutines. Again, array dimensioning must be maintained. Restart files, if requested, are automatically written every load step when using the dynamic relaxation analysis option.

3.3 Input Specifications

INCLUDE FOR ALL DATA SETS

Card Type I   Title Card (20A4)

```
1        6        11       16       21       26       31       36
+-----------------------------------------------------------------------+
| TITLE                                                                 |
+-----------------------------------------------------------------------+

41       46       51       56       61       66       71       76
+-----------------------------------------------------------------------+
|                                                                       |
+-----------------------------------------------------------------------+
```

Columns	Variable	Description
1-80	TITLE	Any 80 alphanumeric characters to identify the run. These characters will be printed as a heading to the output. If the word "RESTART" is in the first seven columns, the job is assumed to be a restart.

INCLUDE FOR ALL DATA SETS

Card Type II   Parameter Card (6I5,E10.6,2I5,E10.6,3I5)

```
1         6         11        16        21        26        31        36
+---------+---------+---------+---------+---------+---------+-------------------+
| NUMNP   | NUMEL   | NUMMAT  | NUMDIS  | MXSTEP  | NDGREE  | DELT              |
+---------+---------+---------+---------+---------+---------+-------------------+

41        46        51        56        61        66        71        76
+---------+---------+-------------------+---------+---------+---------+---------+
| NPRES   | NSLID   | TIMEND            | NPRO    | NEXPC   | NXSTEP  |         |
+---------+---------+-------------------+---------+---------+---------+---------+
```

Columns	Variable	Description
1-5	NUMNP	Number of nodes in the mesh.
6-10	NUMEL	Number of elements in the mesh.
11-15	NUMMAT	Number of different material types; if beam and shell elements are of the same material, they must still be associated with different material types.
16-20	NUMDIS	Number of nodes at which any displacement components are specified a zero or nonzero value. Also indicates number of Type VII cards needed.
21-25	MXSTEP	Number of time steps or load increments. Not necessary if DELT is to be computed by the code.
26-30	NDGREE	Number of degrees of freedom per node. (Currently, can be 2 or 3).
31-40	DELT	Time step, sec or load increment. If the code is to compute the time step, input a negative value (-0.8 to -0.9 recommended) for DELT that will represent the reduced value of the stable time step.
41-45	NPRES	Number of different load lines of the mesh.
46-50	NSLID	Number of sliding interfaces for the mesh. (Not operational in implicit solution).
51-60	TIMEND	Duration of simulation. Use only when DELT is to be computed by the code.
61-65	NPRO	Number of prestress tendons in the mesh.
66-70	NEXPC	Number of elements in the mesh expected to crack. (Default is NUMEL).

(Continue)

Card Type II (Continued)

Columns	Variable	Description
71-75	NXSTEP	Time step number from which restart will begin. Necessary only if the job is a restart. Usually equal to MXSTEP from any previously saved job restart file.

INCLUDE FOR ALL DATA SETS

Card Type III Control Card (16I5)

```
1         6         11        16        21        26        31        36
+---------+---------+---------+---------+---------+---------+---------+---------+
| KON(1)  | KON(2)  | KON(3)  | KON(4)  | KON(5)  | KON(6)  | KON(7)  | KON(8)  |
+---------+---------+---------+---------+---------+---------+---------+---------+

41        46        51        56        61        66        71        76
+---------+---------+---------+---------+---------+---------+---------+---------+
| KON(9)  | KON(10) | KON(11) | KON(12) | KON(13) | KON(14) | KON(15) | KON(16) |
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Columns	Variable	Description
1-5	KONTRL(1)	Analysis option. KONTRL(1)=0: initial velocity analysis option. KONTRL(1)=1: transient analysis option. KONTRL(1)=2: dynamic relaxation analysis option.
6-10	KONTRL(2)	Integration solution option. KONTRL(2)=0: explicit solution.
11-15	KONTRL(3)	Nonequispaced mesh option. KONTRL(3)=0: any nodes for which node cards are not included will be equispaced. KONTRL(3)>0: nodes for which node cards are not included will be spaced so that the ratio of distances between consecutive nodes is KONTRL(3)/1000.
16-20	KONTRL(4)	Percent of stiffness-proportional damping.
21-25	KONTRL(5)	Percent of mass-proportional damping.
26-30	KONTRL(6)	Gravity load option. KONTRL(6)=0: no gravity loading. KONTRL(6)=1: include gravity loading.
31-35	KONTRL(7)	blank.

(Continue)

Card Type III (Continued)

Columns	Variable	Description
36-40	KONTRL(8)	Option for reading or writing data for restart of a job on UNIT 12. KONTRL(8)=0: no restart write or read. KONTRL(8)=1: write a restart file from which only a read can be made with no further writes allowed. KONTRL(8)=2: write a restart file which permits reads and further writes to be made on an existing or new restart file. KONTRL(8)=3: write a restart file which permits modifications to the load lines and time steps for picture output plus reads and writes as in KONTRL(8)=2.
41-45	KONTRL(9)	First value defining time reduction integration parameter. KONTRL(9) times 10 to the KONTRL(10) power is the complete value. If left blank, it defaults to 1.
46-50	KONTRL(10)	If needed, the second value of the time reduction parameter.
51-55	KONTRL(11)	Request for graphics mesh plots (undeformed or deformed). KONTRL(11)=0: no mesh plots will be made. KONTRL(11)>0: mesh plots will be made.*
56-60	KONTRL(12)	KONTRL(12) = maximum number of iterations per load increment.# KONTRL(12), KONTRL(13) and KONTRL(14) are used only when employing the dynamic relaxation analysis option.
61-65	KONTRL(13)	KONTRL(13)/1.0E4 is the error force criterion allowed in the load increment. KONTRL(13)=100 to 200: (recommended).
66-70	KONTRL(14)	KONTRL(14)/1.0E4 is the displacement error criterion allowed in the load increment. KONTRL(14)=10 to 20: (recommended).

(Continue)

Card Type III (Continued)

Columns	Variable	Description
71-75	KONTRL(15)	Option for printing crack information. KONTRL(15)=0: no printing of crack information. (stress limit exceeded cracking). KONTRL(15)=1: print crack information. (stress limit exceeded cracking). KONTRL(15)=2: no printing of crack information. (solution uses cracking control). KONTRL(15)=3: print crack information. (solution uses cracking control).
76-80	KONTRL(16)	blank.

*Undeformed and/or deformed mesh plots are available. Undeformed plots are given at the zero cycle picture output (see Card Type Xd). Deformed plots are given at certain requested cycles (see Card Type Xd). The scale for deformed plots is set by the undeformed (or first requested) plot so that they may be overlayed to view the deformation. If desired, all plotted displacements may be magnified by the value indicated in KONTRL(11); for no magnification, set KONTRL(11)=1.

#Most simulations will take a few hundred to a thousand iterations to meet the error force and displacement error criteria. Simulations which need to capture extreme nonlinear behavior could take several tens of thousands of iterations.

INCLUDE ONLY IF USING BEAM ELEMENTS

Card Type IVa-1 Material Property Card (2I5) Beam Element

```
1         6         11        16        21        26        31        36
+---------+---------+---------------------------------------------------+
| MTYP    | LTYP    |                                                   |
+---------+---------+---------------------------------------------------+

41        46        51        56        61        66        71        76
+-----------------------------------------------------------------------+
|                                                                       |
+-----------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	MTYP	Material type number.
6-10	LTYP	Element type number. LTYP=1: beam element.

INCLUDE ONLY IF USING BEAM ELEMENTS

Card Type IVb-1   Material Property Card (8E10.4) Beam Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(1)              | E(2)              | E(3)              | E(4)              |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(5)              | E(6)              | E(7)              | E(8)              |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(1)	Mass-density.
11-20	E(2)	blank.
21-30	E(3)	Poisson's ratio.
31-40	E(4)	Coefficient of thermal-expansion.
41-50	E(5)	Thermal conductivity.
51-60	E(6)	Specific heat.
61-70	E(7)	Number of temperature curves input for this material on Card Type IVd-1. If E(7) is left blank, default value is 1.0.
71-80	E(8)	Number of stress-strain pairs defining the piecewise linear stress-strain curve. Each temperature curve must have this number of pairs.

INCLUDE ONLY IF USING BEAM ELEMENTS

Card Type IVc-1   Material Property Card (8E10.4) Beam Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(9)              | E(10)             | E(11)             | E(12)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(13)             | E(14)             | E(15)             | E(16)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(9)	Beam width. If left blank, E(9) defaults to unit-width.
11-20	E(10)	Beam thickness (bar area). Input required for NDGREE=3 or bar option. For NDGREE=2 option, thickness can be either specified in dummy node data on Card Type V or input in E(10).
21-30	E(11)	Artificial viscosity.
31-40	E(12)	Effective strain-rate amplitude parameter.
41-50	E(13)	Reference strain-rate.
51-60	E(14)	Plane-stress or plane-strain flag. E(14)=1.0: plane-stress material law. E(14)=2.0: plane-strain material law.
61-70	E(15)	Number of integration points along length. If E(15) is left blank, default value is 2.0. (Currently only acceptable value). For bar option, set E(15)=2.0.
71-80	E(16)	Number of integration points through thickness. If E(16) is left blank, default value is 5.0. If not left blank, E(16)≥2.0. For bar option, set E(16)=1.0.

INCLUDE ONLY IF USING BEAM ELEMENTS

Card Type IVd-1   Material Property Card (8E10.4) Beam Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(17)             | E(18)             | E(19)             | E(20)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(21)             | E(22)             | E(23)             | E(24)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(17)	Temperature-value for curve 1 of piecewise linear stress-strain law.
11-20	E(18)	Young's modulus for temperature value 1.
21-30	E(19)	Strain value for point 1.
31-40	E(20)	Stress value for point 1.
41-50	E(21)	Strain value for point 2.
51-60	E(22)	Stress value for point 2.
61-70	E(23)	Strain value for point 3.
71-80	E(24)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVd-1 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

INCLUDE ONLY IF USING PLANE CONTINUUM ELEMENTS

Card Type IVa-2 Material Property Card (2I5) Plane Continuum Element

```
1         6         11        16        21        26        31        36
+---------+---------+-----------------------------------------------------------+
| MTYP    | LTYP    |                                                           |
+---------+---------+-----------------------------------------------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	MTYP	Material type number.
6-10	LTYP	Element type number. LTYP=2: plane continuum element.

INCLUDE ONLY IF USING PLANE CONTINUUM ELEMENTS

Card Type IVb-2 Material Property Card (8E10.4) Plane Continuum Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(1)              | E(2)              | E(3)              | E(4)              |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(5)              | E(6)              | E(7)              | E(8)              |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(1)	Mass-density.
11-20	E(2)	blank.
21-30	E(3)	Poisson's ratio.
31-40	E(4)	Coefficient of thermal-expansion.
41-50	E(5)	Thermal conductivity.
51-60	E(6)	Specific heat.
61-70	E(7)	Number of temperature curves input for this material on Card Type IVd-2. If E(7) is left blank, default value is 1.0.
71-80	E(8)	Number of stress-strain pairs defining the piecewise linear stress-strain curve. Each temperature curve must have this number of pairs.

INCLUDE ONLY IF USING PLANE CONTINUUM ELEMENTS

Card Type IVc-2 Material Property Card (8E10.4) Plane Continuum Element

```
1       6         11       16        21       26        31       36
+-------------------+-------------------+-------------------+-------------------+
| E(9)              | E(10)             | E(11)             | E(12)             |
+-------------------+-------------------+-------------------+-------------------+

41      46        51       56        61       66        71       76
+-------------------+-------------------+-------------------+-------------------+
| E(13)             | E(14)             | E(15)             | E(16)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(9)	Plane continuum width. If left blank, E(9) defaults to unit-width.
11-20	E(10)	Hourglass viscosity.
21-30	E(11)	Artificial viscosity.
31-40	E(12)	Effective strain-rate amplitude parameter.
41-50	E(13)	Reference strain-rate.
51-60	E(14)	Plane-stress or plane-strain flag. E(14)=11.0: plane-stress material law. E(14)=12.0: plane-strain material law.
61-70	E(15)	blank.
71-80	E(16)	Number of Gaussian integration points along one direction. If E(16) is left blank, default value is 1.0.

INCLUDE ONLY IF USING PLANE CONTINUUM ELEMENTS

Card Type IVd-2   Material Property Card (8E10.4) Plane Continuum Element

```
1        6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(17)             | E(18)             | E(19)             | E(20)             |
+-------------------+-------------------+-------------------+-------------------+

41       46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(21)             | E(22)             | E(23)             | E(24)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(17)	Temperature-value for curve 1 of piecewise linear stress-strain law.
11-20	E(18)	Young's modulus for temperature value 1.
21-30	E(19)	Strain value for point 1.
31-40	E(20)	Stress value for point 1.
41-50	E(21)	Strain value for point 2.
51-60	E(22)	Stress value for point 2.
61-70	E(23)	Strain value for point 3.
71-80	E(24)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVd-2 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

INCLUDE ONLY IF USING PLANE CONCRETE CONTINUUM ELEMENTS

Card Type IVa-3 Material Property Card (2I5) Plane Concrete Element

```
1         6         11        16        21        26        31        36
+---------+---------+-----------------------------------------------------------+
| MTYP    | LTYP    |                                                           |
+---------+---------+-----------------------------------------------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	MTYP	Material type number.
6-10	LTYP	Element type number. LTYP=3: plane concrete element.

INCLUDE ONLY IF USING PLANE CONCRETE CONTINUUM ELEMENTS

Card Type IVb-3   Material Property Card (8E10.4) Plane Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(1)              | E(2)              | E(3)              | E(4)              |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(5)              | E(6)              | E(7)              | E(8)              |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(1)	Mass-density.
11-20	E(2)	Poisson's ratio.
21-30	E(3)	Coefficient of thermal-expansion.*
31-40	E(4)	Stress-dependent thermal expansion coefficient.
41-50	E(5)	Thermal conductivity.*
51-60	E(6)	Specific heat.*
61-70	E(7)	Number of temperature curves input for this material on Card Type IVd-3. If E(7) is left blank, default value is 1.0.
71-80	E(8)	Number of stress-strain pairs defining the piecewise linear stress-strain curve. Each temperature curve must have this number of pairs.

*Property variation with temperature may be imposed by prescribing a negative value in the E-field and providing the temperature-property data at the end of the material cards (Card Type IVi-3 and IVj-3).

INCLUDE ONLY IF USING PLANE CONCRETE CONTINUUM ELEMENTS

Card Type IVc-3   Material Property Card (8E10.4) Plane Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(9)              | E(10)             | E(11)             | E(12)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(13)             | E(14)             | E(15)             | E(16)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(9)	Plane concrete width. If left blank, E(9) defaults to unit-width.
11-20	E(10)	Hourglass viscosity (0.13 recommended for the Belytschko et al. method and any negative value for the Kosloff and Frazier method).
21-30	E(11)	Artificial viscosity.
31-40	E(12)	Mixed hardening parameter. E(12)=0.0: kinematic hardening. 0.0<E(12)<1.0: mixed hardening. E(12)=1.0: isotropic hardening.
41-50	E(13)	Flow rule parameter. E(13)=0.0: associated flow rule (Prager's). E(13)=1.0: nonassociated flow rule (Prager's). E(13)=2.0: associated flow rule (Ziegler's). E(13)=3.0: nonassociated flow rule (Ziegler's).
51-60	E(14)	Plane-stress or plane-strain flag. E(14)=11.0: plane-stress material (first constitutive model). E(14)=12.0: plane-strain material (first constitutive model). E(14)=21.0: plane-stress material (second constitutive model). E(14)=22.0: plane-strain material (second constitutive model).

(Continue)

Card Type IVc-3 (Continued)

Columns	Variable	Description
61-70	E(15)	Failure surface flag. E(15)=0.0: default values (FC=1.0, FT=0.1, FBC=1.15, FPC=0.8, FCC=4.2, GFT=0.0* and GFC=0.0* for the first constitutive model while FC=1.0, FT=0.1, FBC=1.15, FHC=1.3, MUMAX=0.65, LAM1=140 and LAM3/LAM2=10.0 for the second constitutive model). E(15)=1.0: values to be specified at the end of stress-strain pairs (Card Type IVe-3 or IVf-3). E(15)=2.0: pertains to condition E(15)=0.0 with reinforcement (Card Type IVg-3 and IVh-3). E(15)=3.0: pertains to condition E(15)=1.0 with reinforcement (Card Type IVe-3 or IVf-3 with IVg-3 and IVh-3).
71-80	E(16)	Number of Gaussian integration points along one direction (1.0 recommended for cracking).# If E(16) is left blank, default value is 1.0.

*These values imply sudden cracking and crushing for the constitutive model.

#Extensively cracked concrete has problems with hourglass control for one point Gaussian integration and stress locking for two point. This is presently handled by specifying as input one point Gaussian integration and zero hourglass viscosity. This stipulates that an average (one point) material stiffness is employed with two point Gaussian integration to avoid the hourglassing and stress locking conditions.

INCLUDE ONLY IF USING PLANE CONCRETE CONTINUUM ELEMENTS

Card Type IVd-3   Material Property Card (8E10.4) Plane Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(17)             | E(18)             | E(19)             | E(20)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(21)             | E(22)             | E(23)             | E(24)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(17)	Temperature-value for curve 1 of piecewise linear stress-strain law.
11-20	E(18)	Young's modulus for temperature value 1.
21-30	E(19)	Strain value for point 1.
31-40	E(20)	Stress value for point 1.
41-50	E(21)	Strain value for point 2.
51-60	E(22)	Stress value for point 2.
61-70	E(23)	Strain value for point 3.
71-80	E(24)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVd-3 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

If the first constitutive model is used, set the last stress (corresponding to very large strain) equal to the maximum strength of the material under uniaxial compression; if the second constitutive model is used, read in the stress-strain coordinates of the softening portion of the material under uniaxial compression (the program will automatically calculate the exponential coefficient LAM2).

INCLUDE ONLY IF USING PLANE CONCRETE ELEMENTS WITH E(14) < 20.0 AND E(15) = 1.0

Card Type IVe-3   Material Property Card (7E10.4) Plane Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| FC                | FT                | FBC               | FPC               |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| FCC               | GFT               | GFC               |                   |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	FC	Normalized unaxial compressive strength. (S1=S2=0.0 and S3=-FC).
11-20	FT	Normalized unaxial tensile strength. (S1=FT and S2=S3=0.0).
21-30	FBC	Normalized biaxial compressive strength. (S1=0.0 and S2=S3=-FBC).
31-40	FPC	Normalized triaxial compressive strength. (S1=S2=-FPC and S3=-FCC with |FCC|>>|FPC|).
41-50	FCC	Normalized triaxial compressive strength. (S1=S2=-FPC and S3=-FCC with |FCC|>>|FPC|).
51-60	GFT	Fracture energy (force/length) in tension.*
61-70	GFC	Fracture energy (force/length) in compression.*

Absolute values for compression and tension are used in this input. Normalization is with respect to uniaxial compressive strength; i.e., FC=1.0. S1, S2 and S3 are the principal stresses.

*By inputting negative values for GFT and/or GFC (GFT and GFC are now defined as the complete failure strains), the strains for complete failure can be input directly instead of being calculated by the code from the fracture energies. Typical values are approximately five times the peak strains.

INCLUDE ONLY IF USING PLANE CONCRETE ELEMENTS WITH E(14) > 20.0 AND E(15) = 1.0

Card Type IVf-3   Material Property Card (7E10.4) Plane Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| FC                | FT                | FBC               | FHC               |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| MUMAX             | LAM1              | LAM3/LAM2         |                   |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	FC	Uniaxial compressive strength. (S1=S2=0.0 and S3=-FC. Program will calculate FC from the stress-strain input).
11-20	FT	Normalized unaxial tensile strength. (S1=FT and S2=S3=0.0).
21-30	FBC	Normalized biaxial compressive strength. (S1=0.0 and S2=S3=-FBC).
31-40	FHC	Normalized elastic limit for hydrostatic compression. (S1=S2=S3=-FHC).
41-50	MUMAX	Ratio defining the maximum point on the ellipse in the meridian plane. (Use 0.5<MUMAX≤0.66).
51-60	LAM1	Hardening coefficient.
61-70	LAM3/LAM2	Ratio for uniaxial tension/compression softening.

Normalization is with respect to uniaxial compressive strength (S1, S2 and S3 are the principal stresses).

INCLUDE ONLY IF USING PLANE CONCRETE CONTINUUM ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVg-3   Material Property Card (4E10.4) Plane Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| DENS              | THEXP             | NTR               | NSR               |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	DENS	Mass-density for the reinforcement.
11-20	THEXP	Coefficient of thermal-expansion* for the reinforcement.
21-30	NTR	Number of temperature curves for the reinforcement.
31-40	NSR	Number of strain-stress pairs.

*Property variation with temperature may be imposed by prescribing a negative value for THEXP and providing the temperature-property data at the end of the material cards (Card Type IVi-3 and IVj-3).

INCLUDE ONLY IF USING PLANE CONCRETE CONTINUUM ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVh-3   Material Property Card (8E10.4) Plane Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| ER(1)             | ER(2)             | ER(3)             | ER(4)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| ER(5)             | ER(6)             | ER(7)             | ER(8)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	ER(1)	Temperature-value for curve 1 of piecewise linear stress-strain law representing the reinforcement.
11-20	ER(2)	Young's modulus for temperature value 1.
21-30	ER(3)	Strain value for point 1.
31-40	ER(4)	Stress value for point 1.
41-50	ER(5)	Strain value for point 2.
51-60	ER(6)	Stress value for point 2.
61-70	ER(7)	Strain value for point 3.
71-80	ER(8)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVh-3 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

INCLUDE ONLY IF USING PLANE CONCRETE CONTINUUM ELEMENTS WITH THERMAL VARIATION

Card Type IVi-3   Material Property Card (E10.4) Plane Concrete Element

```
1        6        11       16       21       26       31       36
+-------------------+--------------------------------------------------------------+
| NPP               |                                                              |
+-------------------+--------------------------------------------------------------+

41       46       51       56       61       66       71       76
+----------------------------------------------------------------------------------+
|                                                                                  |
+----------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	NPP	Number of temperature-property points.

INCLUDE ONLY IF USING PLANE CONCRETE CONTINUUM ELEMENTS WITH THERMAL VARIATION

Card Type IVj-3 Material Property Card (8E10.4) Plane Concrete Element

```
1    6    11   16   21   26   31   36
+---------+---------+---------+---------+
| EP(1)   | EP(2)   | EP(3)   | EP(4)   |
+---------+---------+---------+---------+

41   46   51   56   61   66   71   76
+---------+---------+---------+---------+
| EP(5)   | EP(6)   | EP(7)   | EP(8)   |
+---------+---------+---------+---------+
```

Columns	Variable	Description
1-10	EP(1)	Temperature value for point 1.
11-20	EP(2)	Property value for point 1.
21-30	EP(3)	Temperature value for point 2.
31-40	EP(4)	Property value for point 2.
41-50	EP(5)	Temperature value for point 3.
51-60	EP(6)	Property value for point 3.
61-70	EP(7)	Temperature value for point 4.
71-80	EP(8)	Property value for point 4.

If less than four points desired, leave the field blank.

Additional Type IVj-3 cards may be used if more temperature-property points are desired to describe the property.

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS

Card Type IVa-4   Material Property Card (2I5) Concrete Beam Element

```
1         6         11        16        21        26        31        36
+---------+---------+-------------------------------------------------------------------+
| MTYP    | LTYP    |                                                                   |
+---------+---------+-------------------------------------------------------------------+

41        46        51        56        61        66        71        76
+---------------------------------------------------------------------------------------+
|                                                                                       |
+---------------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	MTYP	Material type number.
6-10	LTYP	Element type number. LTYP=4: concrete beam element.

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS

Card Type IVb-4   Material Property Card (8E10.4) Concrete Beam Element

```
1        6        11       16       21       26       31       36
+-------------------+-------------------+-------------------+-------------------+
| E(1)              | E(2)              | E(3)              | E(4)              |
+-------------------+-------------------+-------------------+-------------------+

41       46       51       56       61       66       71       76
+-------------------+-------------------+-------------------+-------------------+
| E(5)              | E(6)              | E(7)              | E(8)              |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(1)	Mass-density.
11-20	E(2)	Poisson's ratio.
21-30	E(3)	Coefficient of thermal-expansion.*
31-40	E(4)	Stress-dependent thermal expansion coefficient.
41-50	E(5)	Thermal conductivity.*
51-60	E(6)	Specific heat.*
61-70	E(7)	Number of temperature curves input for this material on Card Type IVd-4. If E(7) is left blank, default value is 1.0.
71-80	E(8)	Number of stress-strain pairs defining the piecewise linear stress-strain curve. Each temperature curve must have this number of pairs.

*Property variation with temperature may be imposed by prescribing a negative value in the E-field and providing the temperature-property data at the end of the material cards (Card Type IVk-4 and IVl-4).

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS

Card Type IVc-4   Material Property Card (8E10.4) Concrete Beam Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(9)              | E(10)             | E(11)             | E(12)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(13)             | E(14)             | E(15)             | E(16)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(9)	Beam width. If left blank, E(9) defaults to unit-width.
11-20	E(10)	Beam thickness (bar area). Input required for NDGREE=3 or bar option. For NDGREE=2 option, thickness can be either specified in dummy node data on Card Type V or input in E(10).
21-30	E(11)	Artificial viscosity.
31-40	E(12)	Mixed hardening parameter. E(12)=0.0: kinematic hardening. 0.0<E(12)<1.0: mixed hardening. E(12)=1.0: isotropic hardening.
41-50	E(13)	Flow rule parameter. E(13)=0.0: associated flow rule (Prager's). E(13)=1.0: nonassociated flow rule (Prager's). E(13)=2.0: associated flow rule (Ziegler's). E(13)=3.0: nonassociated flow rule (Ziegler's).
51-60	E(14)	Plane-stress or plane-strain flag. E(14)=11.0: plane-stress material (first constitutive model). E(14)=12.0: plane-strain material (first constitutive model). E(14)=21.0: plane-stress material (second constitutive model). E(14)=22.0: plane-strain material (second constitutive model).

(Continue)

Card Type IVc-4 (Continued)

Columns	Variable	Description
61-70	E(15)	Failure surface flag. E(15)=0.0: default values (FC=1.0, FT=0.1, FBC=1.15, FPC=0.8, FCC=4.2, GFT=0.0* and GFC=0.0* for the first constitutive model while FC=1.0, FT=0.1, FBC=1.15, FHC=1.3, MUMAX=0.65, LAM1=140 and LAM3/LAM2=10.0 for the second constitutive model). E(15)=1.0: values to be specified at the end of stress-strain pairs (Card Type IVe-4 or IVf-4). E(15)=2.0: pertains to condition E(15)=0.0 with reinforcement (Card Type IVg-4 and IVh-4). E(15)=3.0: pertains to condition E(15)=1.0 with reinforcement (Card Type IVe-4 or IVf-4 with IVg-4 and IVh-4).
71-80	E(16)	Number of integration points through thickness. If E(16) is left blank, default value is 5.0. If not left blank, E(16)≥2.0. For bar option, set E(16)=1.0.

*These values imply sudden cracking and crushing for the constitutive model.

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS

Card Type IVd-4   Material Property Card (8E10.4) Concrete Beam Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(17)             | E(18)             | E(19)             | E(20)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(21)             | E(22)             | E(23)             | E(24)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(17)	Temperature-value for curve 1 of piecewise linear stress-strain law.
11-20	E(18)	Young's modulus for temperature value 1.
21-30	E(19)	Strain value for point 1.
31-40	E(20)	Stress value for point 1.
41-50	E(21)	Strain value for point 2.
51-60	E(22)	Stress value for point 2.
61-70	E(23)	Strain value for point 3.
71-80	E(24)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVd-4 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

If the first constitutive model is used, set the last stress (corresponding to very large strain) equal to the maximum strength of the material under uniaxial compression; if the second constitutive model is used, read in the stress-strain coordinates of the softening portion of the material under uniaxial compression (the program will automatically calculate the exponential coefficient LAM2).

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS WITH E(14) < 20.0 AND E(15) = 1.0

Card Type IVe-4   Material Property Card (7E10.4) Concrete Beam Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| FC                | FT                | FBC               | FPC               |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| FCC               | GFT               | GFC               |                   |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	FC	Normalized unaxial compressive strength. (S1=S2=0.0 and S3=-FC).
11-20	FT	Normalized unaxial tensile strength. (S1=FT and S2=S3=0.0).
21-30	FBC	Normalized biaxial compressive strength. (S1=0.0 and S2=S3=-FBC).
31-40	FPC	Normalized triaxial compressive strength. (S1=S2=-FPC and S3=-FCC with |FCC|>>|FPC|).
41-50	FCC	Normalized triaxial compressive strength. (S1=S2=-FPC and S3=-FCC with |FCC|>>|FPC|).
51-60	GFT	Fracture energy (force/length) in tension.*
61-70	GFC	Fracture energy (force/length) in conpression.*

Absolute values for compression and tension are used in this input. Normalization is with respect to uniaxial compressive strength; i.e., FC=1.0. S1, S2 and S3 are the principal stresses.

*By inputting negative values for GFT and/or GFC (GFT and GFC are now defined as the complete failure strains), the strains for complete failure can be input directly instead of being calculated by the code from the fracture energies. Typical values are approximately five times the peak strains.

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS WITH E(14) > 20.0 AND E(15) = 1.0

Card Type IVf-4   Material Property Card (7E10.4) Concrete Beam Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| FC                | FT                | FBC               | FHC               |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| MUMAX             | LAM1              | LAM3/LAM2         |                   |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	FC	Uniaxial compressive strength. (S1=S2=0.0 and S3=-FC. Program will calculate FC from the stress-strain input).
11-20	FT	Normalized unaxial tensile strength. (S1=FT and S2=S3=0.0).
21-30	FBC	Normalized biaxial compressive strength. (S1=0.0 and S2=S3=-FBC).
31-40	FHC	Normalized elastic limit for hydrostatic compression. (S1=S2=S3=-FHC).
41-50	MUMAX	Ratio defining the maximum point on the ellipse in the meridian plane. (Use $0.5<\text{MUMAX}\leq 0.66$).
51-60	LAM1	Hardening coefficient.
61-70	LAM3/LAM2	Ratio for uniaxial tension/compression softening.

Normalization is with respect to uniaxial compressive strength (S1, S2 and S3 are the principal stresses).

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVg-4   Material Property Card (4E10.4) Concrete Beam Element

```
1        6        11       16       21       26       31       36
+-------------------+-------------------+-------------------+-------------------+
| DENS              | THEXP             | NTR               | NSR               |
+-------------------+-------------------+-------------------+-------------------+

41       46       51       56       61       66       71       76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	DENS	Mass-density for the reinforcement.
11-20	THEXP	Coefficient of thermal-expansion* for the reinforcement.
21-30	NTR	Number of temperature curves for the reinforcement.
31-40	NSR	Number of strain-stress pairs.

*Property variation with temperature may be imposed by prescribing a negative value for THEXP and providing the temperature-property data at the end of the material cards (Card Type IVk-4 and IVl-4).

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVh-4   Material Property Card (8E10.4) Concrete Beam Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| ER(1)             | ER(2)             | ER(3)             | ER(4)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| ER(5)             | ER(6)             | ER(7)             | ER(8)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	ER(1)	Temperature-value for curve 1 of piecewise linear stress-strain law representing the reinforcement.
11-20	ER(2)	Young's modulus for temperature value 1.
21-30	ER(3)	Strain value for point 1.
31-40	ER(4)	Stress value for point 1.
41-50	ER(5)	Strain value for point 2.
51-60	ER(6)	Stress value for point 2.
61-70	ER(7)	Strain value for point 3.
71-80	ER(8)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVh-4 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVi-4   Material Property Card (E10.4) Concrete Beam Element

```
1       6       11      16      21      26      31      36
+-------------------+-----------------------------------------------------------+
| NRB               |                                                           |
+-------------------+-----------------------------------------------------------+

41      46      51      56      61      66      71      76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	NRB	Number of reinforcing layers.

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVj-4   Material Property Card (3E10.4) Concrete Beam Element

```
1        6         11       16        21       26        31       36
+-------------------+-------------------+-------------------+-------------------+
| AREA              | ARM               | ANG               |                   |
+-------------------+-------------------+-------------------+-------------------+

41       46        51       56        61       66        71       76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	AREA	Area of reinforcing bar in the specified layer. (Use AREA=-AREA if this layer represents shear ties).
11-20	ARM	Distance of specified reinforcing layer from local x-axis.* (Use negative value if the layer is in a negative direction from the local x-axis).
21-30	ANG	Identification of reinforcement. ANG=0.0: reinforcement parallel to local x-axis. If negative AREA, angular alignment of shear tie layer with respect to the beam's local x-axis. 0.0<ANG<90.0: angular alignment of shear tie.

*The local x-axis is defined by the element connectivity (see Card Type Xc).

Use as many cards as there are layers specified by NRB on Card Type IVi-4.

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS WITH THERMAL VARIATION

Card Type IVk-4   Material Property Card (E10.4) Concrete Beam Element

```
1        6         11       16       21       26       31       36
+-------------------+-----------------------------------------------------+
| NPP               |                                                     |
+-------------------+-----------------------------------------------------+

41       46        51       56       61       66       71       76
+-------------------------------------------------------------------------+
|                                                                         |
+-------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	NPP	Number of temperature-property points.

INCLUDE ONLY IF USING CONCRETE BEAM ELEMENTS WITH THERMAL VARIATION

Card Type IV1-4   Material Property Card (8E10.4) Concrete Beam Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| EP(1)             | EP(2)             | EP(3)             | EP(4)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| EP(5)             | EP(6)             | EP(7)             | EP(8)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	EP(1)	Temperature value for point 1.
11-20	EP(2)	Property value for point 1.
21-30	EP(3)	Temperature value for point 2.
31-40	EP(4)	Property value for point 2.
41-50	EP(5)	Temperature value for point 3.
51-60	EP(6)	Property value for point 3.
61-70	EP(7)	Temperature value for point 4.
71-80	EP(8)	Property value for point 4.

If less than four points desired, leave the field blank.

Additional Type IV1-4 cards may be used if more temperature-property points are desired to describe the property.

INCLUDE ONLY IF USING SHELL ELEMENTS

Card Type IVa-11   Material Property Card (2I5) Shell Element

```
1         6         11        16        21        26        31        36
+---------+---------+-------------------------------------------------------------------+
| MTYP    | LTYP    |                                                                   |
+---------+---------+-------------------------------------------------------------------+

41        46        51        56        61        66        71        76
+---------------------------------------------------------------------------------------+
|                                                                                       |
+---------------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	MTYP	Material type number.
6-10	LTYP	Element type number. LTYP=11: shell element.

INCLUDE ONLY IF USING SHELL ELEMENTS

Card Type IVb-11   Material Property Card (8E10.4) Shell Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(1)              | E(2)              | E(3)              | E(4)              |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(5)              | E(6)              | E(7)              | E(8)              |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(1)	Mass-density.
11-20	E(2)	blank.
21-30	E(3)	Poisson's ratio.
31-40	E(4)	Coefficient of thermal-expansion.
41-50	E(5)	Thermal conductivity.
51-60	E(6)	Specific heat.
61-70	E(7)	Number of temperature curves input for this material on Card Type IVd-11. If E(7) is left blank, default value is 1.0.
71-80	E(8)	Number of stress-strain pairs defining the piecewise linear stress-strain curve. Each temperature curve must have this number of pairs.

INCLUDE ONLY IF USING SHELL ELEMENTS

Card Type IVc-11   Material Property Card (8E10.4) Shell Element

```
1       6       11      16      21      26      31      36
+---------------+---------------+---------------+---------------+
| E(9)          | E(10)         | E(11)         | E(12)         |
+---------------+---------------+---------------+---------------+

41      46      51      56      61      66      71      76
+---------------+---------------+---------------+---------------+
| E(13)         | E(14)         | E(15)         | E(16)         |
+---------------+---------------+---------------+---------------+
```

Columns	Variable	Description
1-10	E(9)	blank.
11-20	E(10)	Shell thickness (ring area). Input required for NDGREE=3, membrane or ring option. For NDGREE=2 option, thickness can be either specified in dummy node data on Card Type V or input in E(10).
21-30	E(11)	Artificial viscosity.
31-40	E(12)	Effective strain-rate amplitude parameter.
41-50	E(13)	Reference strain-rate.
51-60	E(14)	Axisymmetric flag. E(14)=3.0: axisymmetric material law.
61-70	E(15)	Number of integration points along length. If E(15) is left blank, default value is 2.0. For ring option, set E(15)=1.0. For membrane option, set E(15)=2.0.
71-80	E(16)	Number of integration points through thickness. If E(16) is left blank, default value is 5.0. If not left blank, E(16)≥2.0. For ring or membrane option, set E(16)=1.0.

INCLUDE ONLY IF USING SHELL ELEMENTS

Card Type IVd-11   Material Property Card (8E10.4) Shell Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(17)             | E(18)             | E(19)             | E(20)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(21)             | E(22)             | E(23)             | E(24)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(17)	Temperature-value for curve 1 of piecewise linear stress-strain law.
11-20	E(18)	Young's modulus for temperature value 1.
21-30	E(19)	Strain value for point 1.
31-40	E(20)	Stress value for point 1.
41-50	E(21)	Strain value for point 2.
51-60	E(22)	Stress value for point 2.
61-70	E(23)	Strain value for point 3.
71-80	E(24)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVd-11 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

INCLUDE ONLY IF USING AXISYMMETRIC CONTINUUM ELEMENTS

Card Type IVa-12   Material Property Card (2I5) Axisymmetric Continuum Element

```
1         6         11        16        21        26        31        36
+---------+---------+-----------------------------------------------------------------+
| MTYP    | LTYP    |                                                                 |
+---------+---------+-----------------------------------------------------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------------+
|                                                                                     |
+-------------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	MTYP	Material type number.
6-10	LTYP	Element type number. LTYP=12: axisymmetric continuum element.

INCLUDE ONLY IF USING AXISYMMETRIC CONTINUUM ELEMENTS

Card Type IVb-12   Material Property Card (8E10.4) Axisymmetric Continuum Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(1)              | E(2)              | E(3)              | E(4)              |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(5)              | E(6)              | E(7)              | E(8)              |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(1)	Mass-density.
11-20	E(2)	blank.
21-30	E(3)	Poisson's ratio.
31-40	E(4)	Coefficient of thermal-expansion.
41-50	E(5)	Thermal conductivity.
51-60	E(6)	Specific heat.
61-70	E(7)	Number of temperature curves input for this material on Card Type IVd-12. If E(7) is left blank, default value is 1.0.
71-80	E(8)	Number of stress-strain pairs defining the piecewise linear stress-strain curve. Each temperature curve must have this number of pairs.

INCLUDE ONLY IF USING AXISYMMETRIC CONTINUUM ELEMENTS

Card Type IVc-12   Material Property Card (8E10.4) Axisymmetric Continuum Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(9)              | E(10)             | E(11)             | E(12)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(13)             | E(14)             | E(15)             | E(16)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(9)	blank.
11-20	E(10)	Hourglass viscosity.
21-30	E(11)	Artificial viscosity.
31-40	E(12)	Effective strain-rate amplitude parameter.
41-50	E(13)	Reference strain-rate.
51-60	E(14)	Axisymmetric flag. E(14)=13.0: axisymmetric material law.
61-70	E(15)	blank.
71-80	E(16)	Number of Gaussian integration points along one direction. If E(16) is left blank, default value is 1.0.

INCLUDE ONLY IF USING AXISYMMETRIC CONTINUUM ELEMENTS

Card Type IVd-12   Material Property Card (8E10.4) Axisymmetric Continuum Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(17)             | E(18)             | E(19)             | E(20)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(21)             | E(22)             | E(23)             | E(24)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(17)	Temperature-value for curve 1 of piecewise linear stress-strain law.
11-20	E(18)	Young's modulus for temperature value 1.
21-30	E(19)	Strain value for point 1.
31-40	E(20)	Stress value for point 1.
41-50	E(21)	Strain value for point 2.
51-60	E(22)	Stress value for point 2.
61-70	E(23)	Strain value for point 3.
71-80	E(24)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVd-12 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

INCLUDE ONLY IF USING AXISYMMETRIC CONCRETE CONTINUUM ELEMENTS

Card Type IVa-13   Material Property Card (2I5) Axisymmetric Concrete Element

```
1         6         11        16        21        26        31        36
+---------+---------+---------------------------------------------------------------+
| MTYP    | LTYP    |                                                               |
+---------+---------+---------------------------------------------------------------+

41        46        51        56        61        66        71        76
+---------------------------------------------------------------------------------+
|                                                                                 |
+---------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	MTYP	Material type number.
6-10	LTYP	Element type number. LTYP=13: axisymmetric concrete element.

INCLUDE ONLY IF USING AXISYMMETRIC CONCRETE CONTINUUM ELEMENTS

Card Type IVb-13   Material Property Card (8E10.4) Axisymmetric Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(1)              | E(2)              | E(3)              | E(4)              |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(5)              | E(6)              | E(7)              | E(8)              |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(1)	Mass-density.
11-20	E(2)	Poisson's ratio.
21-30	E(3)	Coefficient of thermal-expansion.*
31-40	E(4)	Stress-dependent thermal expansion coefficient.
41-50	E(5)	Thermal conductivity.*
51-60	E(6)	Specific heat.*
61-70	E(7)	Number of temperature curves input for this material on Card Type IVd-13. If E(7) is left blank, default value is 1.0.
71-80	E(8)	Number of stress-strain pairs defining the piecewise linear stress-strain curve. Each temperature curve must have this number of pairs.

*Property variation with temperature may be imposed by prescribing a negative value in the E-field and providing the temperature-property data at the end of the material cards (Card Type IVi-13 and IVj-13).

INCLUDE ONLY IF USING AXISYMMETRIC CONCRETE CONTINUUM ELEMENTS

Card Type IVc-13   Material Property Card (8E10.4) Axisymmetric Concrete Element

```
1       6       11      16      21      26      31      36
+---------------+---------------+---------------+---------------+
| E(9)          | E(10)         | E(11)         | E(12)         |
+---------------+---------------+---------------+---------------+

41      46      51      56      61      66      71      76
+---------------+---------------+---------------+---------------+
| E(13)         | E(14)         | E(15)         | E(16)         |
+---------------+---------------+---------------+---------------+
```

Columns	Variable	Description
1-10	E(9)	blank.
11-20	E(10)	Hourglass viscosity (0.13 recommended for the Belytschko et al. method and any negative value for the Kosloff and Frazier method).
21-30	E(11)	Artificial viscosity.
31-40	E(12)	Mixed hardening parameter. E(12)=0.0: kinematic hardening. 0.0<E(12)<1.0: mixed hardening. E(12)=1.0: isotropic hardening.
41-50	E(13)	Flow rule parameter. E(13)=0.0: associated flow rule (Prager's). E(13)=1.0: nonassociated flow rule (Prager's). E(13)=2.0: associated flow rule (Ziegler's). E(13)=3.0: nonassociated flow rule (Ziegler's).
51-60	E(14)	Axisymmetric flag. E(14)=13.0: axisymmetric material law (first constitutive model). E(14)=23.0: axisymmetric material law (second constitutive model).

(Continue)

Card Type IVc-13 (Continued)

Columns	Variable	Description
61-70	E(15)	Failure surface flag. E(15)=0.0: default values (FC=1.0, FT=0.1, FBC=1.15, FPC=0.8, FCC=4.2, GFT=0.0* and GFC=0.0* for the first constitutive model while FC=1.0, FT=0.1, FBC=1.15, FHC=1.3, MUMAX=0.65, LAM1=140 and LAM3/LAM2=10.0 for the second constitutive model). E(15)=1.0: values to be specified at the end of stress-strain pairs (Card Type IVe-13 or IVf-13). E(15)=2.0: pertains to condition E(15)=0.0 with reinforcement (Card Type IVg-13 and IVh-13). E(15)=3.0: pertains to condition E(15)=1.0 with reinforcement (Card Type IVe-13 or IVf-13 with IVg-13 and IVh-13).
71-80	E(16)	Number of Gaussian integration points along one direction (1.0 recommended for cracking).# If E(16) is left blank, default value is 1.0.

*These values imply sudden cracking and crushing for the constitutive model.

#Extensively cracked concrete has problems with hourglass control for one point Gaussian integration and stress locking for two point. This is presently handled by specifying as input one point Gaussian integration and zero hourglass viscosity. This stipulates that an average (one point) material stiffness is employed with two point Gaussian integration to avoid the hourglassing and stress locking conditions.

INCLUDE ONLY IF USING AXISYMMETRIC CONCRETE CONTINUUM ELEMENTS

Card Type IVd-13   Material Property Card (8E10.4) Axisymmetric Concrete Element

```
1       6        11       16       21       26       31       36
+-------------------+-------------------+-------------------+-------------------+
| E(17)             | E(18)             | E(19)             | E(20)             |
+-------------------+-------------------+-------------------+-------------------+

41      46       51       56       61       66       71       76
+-------------------+-------------------+-------------------+-------------------+
| E(21)             | E(22)             | E(23)             | E(24)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(17)	Temperature-value for curve 1 of piecewise linear stress-strain law.
11-20	E(18)	Young's modulus for temperature value 1.
21-30	E(19)	Strain value for point 1.
31-40	E(20)	Stress value for point 1.
41-50	E(21)	Strain value for point 2.
51-60	E(22)	Stress value for point 2.
61-70	E(23)	Strain value for point 3.
71-80	E(24)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVd-13 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

If the first constitutive model is used, set the last stress (corresponding to very large strain) equal to the maximum strength of the material under uniaxial compression; if the second constitutive model is used, read in the stress-strain coordinates of the softening portion of the material under uniaxial compression (the program will automatically calculate the exponential coefficient LAM2).

INCLUDE ONLY IF USING AXISYM CONCRETE ELEMENTS WITH E(14) < 20.0 AND E(15) = 1.0

Card Type IVe-13   Material Property Card (7E10.4) Axisymmetric Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| FC                | FT                | FBC               | FPC               |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| FCC               | GFT               | GFC               |                   |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	FC	Normalized unaxial compressive strength. (S1=S2=0.0 and S3=-FC).
11-20	FT	Normalized unaxial tensile strength. (S1=FT and S2=S3=0.0).
21-30	FBC	Normalized biaxial compressive strength. (S1=0.0 and S2=S3=-FBC).
31-40	FPC	Normalized triaxial compressive strength. (S1=S2=-FPC and S3=-FCC with |FCC|>>|FPC|).
41-50	FCC	Normalized triaxial compressive strength. (S1=S2=-FPC and S3=-FCC with |FCC|>>|FPC|).
51-60	GFT	Fracture energy (force/length) in tension.*
61-70	GFC	Fracture energy (force/length) in conpression.*

Absolute values for compression and tension are used in this input. Normalization is with respect to uniaxial compressive strength; i.e., FC=1.0. S1, S2 and S3 are the principal stresses.

*By inputting negative values for GFT and/or GFC (GFT and GFC are now defined as the complete failure strains), the strains for complete failure can be input directly instead of being calculated by the code from the fracture energies. Typical values are approximately five times the peak strains.

INCLUDE ONLY IF USING AXISYM CONCRETE ELEMENTS WITH E(14) > 20.0 AND E(15) = 1.0

Card Type IVf-13   Material Property Card (7E10.4) Axisymmetric Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| FC                | FT                | FBC               | FHC               |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| MUM               | LAM1              | LAM3/LAM2         |                   |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	FC	Uniaxial compressive strength. (S1=S2=0.0 and S3=-FC. Program will calculate FC from the stress-strain input).
11-20	FT	Normalized unaxial tensile strength. (S1=FT and S2=S3=0.0).
21-30	FBC	Normalized biaxial compressive strength. (S1=0.0 and S2=S3=-FBC).
31-40	FHC	Normalized elastic limit for hydrostatic compression. (S1=S2=S3=-FHC).
41-50	MUMAX	Ratio defining the maximum point on the ellipse in the meridian plane. (Use 0.5<MUMAX≤0.66).
51-60	LAM1	Hardening coefficient.
61-70	LAM3/LAM2	Ratio for uniaxial tension/compression softening.

Normalization is with respect to uniaxial compressive strength (S1, S2 and S3 are the principal stresses).

INCLUDE ONLY IF USING AXISYM CONCRETE CONTINUUM ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVg-13   Material Property Card (4E10.4) Axisymmetric Concrete Element

```
1        6        11       16       21       26       31       36
+-------------------+-------------------+-------------------+-------------------+
| DENS              | THEXP             | NTR               | NSR               |
+-------------------+-------------------+-------------------+-------------------+

41       46       51       56       61       66       71       76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	DENS	Mass-density for the reinforcement.
11-20	THEXP	Coefficient of thermal-expansion* for the reinforcement.
21-30	NTR	Number of temperature curves for the reinforcement.
31-40	NSR	Number of strain-stress pairs.

*Property variation with temperature may be imposed by prescribing a negative value for THEXP and providing the temperature-property data at the end of the material cards (Card Type IVi-13 and IVj-13).

INCLUDE ONLY IF USING AXISYM CONCRETE CONTINUUM ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVh-13   Material Property Card (8E10.4) Axisymmetric Concrete Element

```
1       6       11      16      21      26      31      36
+---------------+---------------+---------------+---------------+
| ER(1)         | ER(2)         | ER(3)         | ER(4)         |
+---------------+---------------+---------------+---------------+

41      46      51      56      61      66      71      76
+---------------+---------------+---------------+---------------+
| ER(5)         | ER(6)         | ER(7)         | ER(8)         |
+---------------+---------------+---------------+---------------+
```

Columns	Variable	Description
1-10	ER(1)	Temperature-value for curve 1 of piecewise linear stress-strain law representing the reinforcement.
11-20	ER(2)	Young's modulus for temperature value 1.
21-30	ER(3)	Strain value for point 1.
31-40	ER(4)	Stress value for point 1.
41-50	ER(5)	Strain value for point 2.
51-60	ER(6)	Stress value for point 2.
61-70	ER(7)	Strain value for point 3.
71-80	ER(8)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVh-13 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

INCLUDE ONLY IF USING AXISYM CONCRETE CONTINUUM ELEMENTS WITH THERMAL VARIATION

Card Type IVi-13   Material Property Card (E10.4) Axisymmetric Concrete Element

```
1         6         11        16        21        26        31        36
+-------------------+-----------------------------------------------------------+
| NPP               |                                                           |
+-------------------+-----------------------------------------------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	NPP	Number of temperature-property points.

INCLUDE ONLY IF USING AXISYM CONCRETE CONTINUUM ELEMENTS WITH THERMAL VARIATION

Card Type IVj-13 Material Property Card (8E10.4) Axisymmetric Concrete Element

```
1       6       11      16      21      26      31      36
+-------------------+-------------------+-------------------+-------------------+
| EP(1)             | EP(2)             | EP(3)             | EP(4)             |
+-------------------+-------------------+-------------------+-------------------+

41      46      51      56      61      66      71      76
+-------------------+-------------------+-------------------+-------------------+
| EP(5)             | EP(6)             | EP(7)             | EP(8)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	EP(1)	Temperature value for point 1.
11-20	EP(2)	Property value for point 1.
21-30	EP(3)	Temperature value for point 2.
31-40	EP(4)	Property value for point 2.
41-50	EP(5)	Temperature value for point 3.
51-60	EP(6)	Property value for point 3.
61-70	EP(7)	Temperature value for point 4.
71-80	EP(8)	Property value for point 4.

If less than four points desired, leave the field blank.

Additional Type IVj-13 cards may be used if more temperature-property points are desired to describe the property.

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS

Card Type IVa-14   Material Property Card (2I5) Concrete Shell Element

```
1         6         11        16        21        26        31        36
+---------+---------+-------------------------------------------------------+
| MTYP    | LTYP    |                                                       |
+---------+---------+-------------------------------------------------------+

41        46        51        56        61        66        71        76
+---------------------------------------------------------------------------+
|                                                                           |
+---------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	MTYP	Material type number.
6-10	LTYP	Element type number. LTYP=14: concrete shell element.

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS

Card Type IVb-14   Material Property Card (8E10.4) Concrete Shell Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(1)              | E(2)              | E(3)              | E(4)              |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(5)              | E(6)              | E(7)              | E(8)              |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(1)	Mass-density.
11-20	E(2)	Poisson's ratio.
21-30	E(3)	Coefficient of thermal-expansion.*
31-40	E(4)	Stress-dependent thermal expansion coefficient.
41-50	E(5)	Thermal conductivity.*
51-60	E(6)	Specific heat.*
61-70	E(7)	Number of temperature curves input for this material on Card Type IVd-14. If E(7) is left blank, default value is 1.0.
71-80	E(8)	Number of stress-strain pairs defining the piecewise linear stress-strain curve. Each temperature curve must have this number of pairs.

*Property variation with temperature may be imposed by prescribing a negative value in the E-field and providing the temperature-property data at the end of the material cards (Card Type IVk-14 and IVl-14).

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS

Card Type IVc-14   Material Property Card (8E10.4) Concrete Shell Element

```
1       6       11      16      21      26      31      36
+---------------+---------------+---------------+---------------+
| E(9)          | E(10)         | E(11)         | E(12)         |
+---------------+---------------+---------------+---------------+

41      46      51      56      61      66      71      76
+---------------+---------------+---------------+---------------+
| E(13)         | E(14)         | E(15)         | E(16)         |
+---------------+---------------+---------------+---------------+
```

Columns	Variable	Description
1-10	E(9)	blank.
11-20	E(10)	Shell thickness (ring area). Input required for NDGREE=3, membrane or ring option. For NDGREE=2 option, thickness can be either specified in dummy node data on Card Type V or input in E(10).
21-30	E(11)	Artificial viscosity.
31-40	E(12)	Mixed hardening parameter. E(12)=0.0: kinematic hardening. 0.0<E(12)<1.0: mixed hardening. E(12)=1.0: isotropic hardening.
41-50	E(13)	Flow rule parameter. E(13)=0.0: associated flow rule (Prager's). E(13)=1.0: nonassociated flow rule (Prager's). E(13)=2.0: associated flow rule (Ziegler's). E(13)=3.0: nonassociated flow rule (Ziegler's).
51-60	E(14)	Axisymmetric flag. E(14)=13.0: axisymmetric material law (first constitutive model). E(14)=23.0: axisymmetric material law (second constitutive model).

(Continue)

Card Type IVc-14 (Continued)

Columns	Variable	Description
61-70	E(15)	Failure surface flag. E(15)=0.0: default values (FC=1.0, FT=0.1, FBC=1.15, FPC=0.8, FCC=4.2, GFT=0.0* and GFC=0.0* for the first constitutive model while FC=1.0, FT=0.1, FBC=1.15, FHC=1.3, MUMAX=0.65, LAM1=140 and LAM3/LAM2=10.0 for the second constitutive model). E(15)=1.0: values to be specified at the end of stress-strain pairs (Card Type IVe-14 or IVf-14). E(15)=2.0: pertains to condition E(15)=0.0 with reinforcement (Card Type IVg-14 and IVh-14). E(15)=3.0: pertains to condition E(15)=1.0 with reinforcement (Card Type IVe-14 or IVf-14 with IVg-14 and IVh-14).
71-80	E(16)	Number of integration points through thickness. If E(16) is left blank, default value is 5.0. If not left blank, E(16)≥2.0. For ring or membrane option, set E(16)=1.0.

*These values imply sudden cracking and crushing for the constitutive model.

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS

Card Type IVd-14   Material Property Card (8E10.4) Concrete Shell Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| E(17)             | E(18)             | E(19)             | E(20)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| E(21)             | E(22)             | E(23)             | E(24)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	E(17)	Temperature-value for curve 1 of piecewise linear stress-strain law.
11-20	E(18)	Young's modulus for temperature value 1.
21-30	E(19)	Strain value for point 1.
31-40	E(20)	Stress value for point 1.
41-50	E(21)	Strain value for point 2.
51-60	E(22)	Stress value for point 2.
61-70	E(23)	Strain value for point 3.
71-80	E(24)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVd-14 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

If the first constitutive model is used, set the last stress (corresponding to very large strain) equal to the maximum strength of the material under uniaxial compression; if the second constitutive model is used, read in the stress-strain coordinates of the softening portion of the material under uniaxial compression (the program will automatically calculate the exponential coefficient LAM2).

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS WITH E(14) < 20.0 AND E(15) = 1.0

Card Type IVe-14   Material Property Card (7E10.4) Concrete Shell Element

```
1       6       11      16      21      26      31      36
+-------------------+-------------------+-------------------+-------------------+
| FC                | FT                | FBC               | FPC               |
+-------------------+-------------------+-------------------+-------------------+

41      46      51      56      61      66      71      76
+-------------------+-------------------+-------------------+-------------------+
| FCC               | GFT               | GFC               |                   |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	FC	Normalized unaxial compressive strength. (S1=S2=0.0 and S3=-FC).
11-20	FT	Normalized unaxial tensile strength. (S1=FT and S2=S3=0.0).
21-30	FBC	Normalized biaxial compressive strength. (S1=0.0 and S2=S3=-FBC).
31-40	FPC	Normalized triaxial compressive strength. (S1=S2=-FPC and S3=-FCC with |FCC|>>|FPC|).
41-50	FCC	Normalized triaxial compressive strength. (S1=S2=-FPC and S3=-FCC with |FCC|>>|FPC|).
51-60	GFT	Fracture energy (force/length) in tension.*
61-70	GFC	Fracture energy (force/length) in conpression.*

Absolute values for compression and tension are used in this input. Normalization is with respect to uniaxial compressive strength; i.e., FC=1.0. S1, S2 and S3 are the principal stresses.

*By inputting negative values for GFT and/or GFC (GFT and GFC are now defined as the complete failure strains), the strains for complete failure can be input directly instead of being calculated by the code from the fracture energies. Typical values are approximately five times the peak strains.

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS WITH E(14) > 20.0 AND E(15) = 1.0

Card Type IVf-14   Material Property Card (7E10.4) Concrete Shell Element

```
1        6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| FC                | FT                | FBC               | FHC               |
+-------------------+-------------------+-------------------+-------------------+

41       46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| MUMAX             | LAM1              | LAM3/LAM2         |                   |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	FC	Uniaxial compressive strength. (S1=S2=0.0 and S3=-FC. Program will calculate FC from the stress-strain input).
11-20	FT	Normalized unaxial tensile strength. (S1=FT and S2=S3=0.0).
21-30	FBC	Normalized biaxial compressive strength. (S1=0.0 and S2=S3=-FBC).
31-40	FHC	Normalized elastic limit for hydrostatic compression. (S1=S2=S3=-FHC).
41-50	MUMAX	Ratio defining the maximum point on the ellipse in the meridian plane. (Use 0.5<MUMAX≤0.66).
51-60	LAM1	Hardening coefficient.
61-70	LAM3/LAM2	Ratio for uniaxial tension/compression softening.

Normalization is with respect to uniaxial compressive strength (S1, S2 and S3 are the principal stresses).

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVg-14   Material Property Card (4E10.4) Concrete Shell Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| DENS              | THEXP             | NTR               | NSR               |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	DENS	Mass-density for the reinforcement.
11-20	THEXP	Coefficient of thermal-expansion* for the reinforcement.
21-30	NTR	Number of temperature curves for the reinforcement.
31-40	NSR	Number of strain-stress pairs.

*Property variation with temperature may be imposed by prescribing a negative value for THEXP and providing the temperature-property data at the end of the material cards (Card Type IVk-14 and IVl-14).

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVh-14   Material Property Card (8E10.4) Concrete Shell Element

```
1        6        11       16       21       26       31       36
+-------------------+-------------------+-------------------+-------------------+
| ER(1)             | ER(2)             | ER(3)             | ER(4)             |
+-------------------+-------------------+-------------------+-------------------+

41       46       51       56       61       66       71       76
+-------------------+-------------------+-------------------+-------------------+
| ER(5)             | ER(6)             | ER(7)             | ER(8)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	ER(1)	Temperature-value for curve 1 of piecewise linear stress-strain law representing the reinforcement.
11-20	ER(2)	Young's modulus for temperature value 1.
21-30	ER(3)	Strain value for point 1.
31-40	ER(4)	Stress value for point 1.
41-50	ER(5)	Strain value for point 2.
51-60	ER(6)	Stress value for point 2.
61-70	ER(7)	Strain value for point 3.
71-80	ER(8)	Stress value for point 3.

If less than three points desired, leave the field blank.

Additional Type IVh-14 cards may be used if more stress-strain points are desired to describe the material or if more than one temperature curve is desired. No limit on number of points or temperature curves.

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVi-14   Material Property Card (E10.4) Concrete Shell Element

```
1         6         11        16        21        26        31        36
+-------------------+---------------------------------------------------------+
| NRB               |                                                         |
+-------------------+---------------------------------------------------------+

41        46        51        56        61        66        71        76
+-----------------------------------------------------------------------------+
|                                                                             |
+-----------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	NRB	Number of reinforcing layers.

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS WITH E(15) = 2.0 OR 3.0

Card Type IVj-14   Material Property Card (3E10.4) Concrete Shell Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| AREA              | ARM               | ANG               |                   |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	AREA	Area of reinforcing bar in the specified layer. (Use AREA=-AREA if this layer represents shear ties).
11-20	ARM	Distance of specified reinforcing layer from local x-axis.* (Use negative value if the layer is in a negative direction from the local x-axis).
21-30	ANG	Identification of reinforcement within the meridional-circumferential plane. ANG=0.0: meridional reinforcement. 0.0<|ANG|<90.0: 'seismic' reinforcement. ANG=90.0: hoop reinforcement. If negative AREA, angular alignment of shear tie layer with respect to the shell's local x-axis. 0.0<ANG<90.0: angular alignment of shear tie.

*The local x-axis is defined by the element connectivity (see Card Type Xc).

Use as many cards as there are layers specified by NRB on Card Type IVi-14.

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS WITH THERMAL VARIATION

Card Type IVk-14   Material Property Card (E10.4) Concrete Shell Element

```
1        6         11        16        21        26        31        36
+-------------------+-------------------------------------------------------------+
| NPP               |                                                             |
+-------------------+-------------------------------------------------------------+

41       46        51        56        61        66        71        76
+---------------------------------------------------------------------------------+
|                                                                                 |
+---------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	NPP	Number of temperature-property points.

INCLUDE ONLY IF USING CONCRETE SHELL ELEMENTS WITH THERMAL VARIATION

Card Type IV1-14   Material Property Card (8E10.4) Concrete Shell Element

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| EP(1)             | EP(2)             | EP(3)             | EP(4)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| EP(5)             | EP(6)             | EP(7)             | EP(8)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	EP(1)	Temperature value for point 1.
11-20	EP(2)	Property value for point 1.
21-30	EP(3)	Temperature value for point 2.
31-40	EP(4)	Property value for point 2.
41-50	EP(5)	Temperature value for point 3.
51-60	EP(6)	Property value for point 3.
61-70	EP(7)	Temperature value for point 4.
71-80	EP(8)	Property value for point 4.

If less than four points desired, leave the field blank.

Additional Type IV1-14 cards may be used if more temperature-property points are desired to describe the property.

INCLUDE FOR ALL DATA SETS

Card Type V Node Card (2I5,4E10.4)

```
1         6         11        16        21        26        31        36
+---------+---------+-------------------+-------------------+-------------------+
| N       | M       | XC(N)             | YC(N)             | XSHIFT            |
+---------+---------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-----------------------------------------------------------+
| YSHIFT            |                                                           |
+-------------------+-----------------------------------------------------------+
```

Columns	Variable	Description
1-5	N	Node number.
6-10	M	Coordinate system used for this sequence of nodes. Input may be a mix of cartesian and polar systems. M=0: cartesian (x, y) system. M=1: polar (r, θ) system.
11-20	XC(N)	x-coordinate (r-coordinate if polar).
21-30	YC(N)	y-coordinate (θ-coordinate if polar).
31-40	XSHIFT	x-coordinate value defining the local origin if using polar system input.
41-50	YSHIFT	y-coordinate value defining the local origin if using polar system input.

Nodal coordinates for nodes equispaced between two nodes will be automatically generated if the data cards for intermediate nodes are skipped. If nonequispaced nodes are to be generated, use KONTRL(3) (see Card Type III).

Coordinate values specified are those for the mid-plane surface of the beam or shell elements.

When using 2 degrees of freedom per node option, a 'dummy' node (for beam or shell elements only) is needed to store the rotation associated with the translation node. The value input for the coordinates would thus be left blank unless one wishes to input the thickness (see Card Type IVc-1) of the beam or shell here instead. The thickness would be specified through the XC(N) coordinate. In that case, the beam or shell thickness used will be the average of the thickness precribed by the beam's or shell's two connecting nodes. If the thickness is specified here, it will override that specified on the material card (see Card Type IVc-1).

When using 3 degrees of freedom per node option (for beam or shell element only), the rotations at this node are the 3rd degree of freedom. The thickness of the beam element must then be stored in E(10) on the material card.

INCLUDE FOR ALL DATA SETS

Card Type VI   Element Card (12I5)

```
1         6         11        16        21        26        31        36
+---------+---------+---------+---------+---------+---------+---------+---------+
| M       | IX(1,M) | IX(2,M) | IX(3,M) | IX(4,M) | IX(5,M) | IX(6,M) | IX(7,M) |
+---------+---------+---------+---------+---------+---------+---------+---------+

41        46        51        56        61        66        71        76
+---------+---------+---------+---------+---------------------------------------+
| IX(8,M) | MTYP    | LTYP    | INCR    |                                       |
+---------+---------+---------+---------+---------------------------------------+
```

Columns	Variable	Description
1-5	M	Element number.
6-10	IX(1,M)	
11-15	IX(2,M)	
16-20	IX(3,M)	
21-25	IX(4,M)	Nodes describing the element (see element description below).
26-30	IX(5,M)	
31-35	IX(6,M)	
36-40	IX(7,M)	
41-45	IX(8,M)	See notes below.
46-50	MTYP	Material type number. See Card Type IVa.
51-55	LTYP	Element type number.
56-60	INCR	Increment to generate IX(J,M) for subsequent elements. If INCR is left blank, default is 1.

<u>Beam or shell elements</u>: IX(1,M) and IX(2,M) are displacement nodes always. For ring option, set IX(2,M)=IX(1,M). IX(3,M) and IX(4,M) are 'dummy' nodes which store rotations for IX(2,M) and IX(1,M), respectively, for NDGREE=2 option. IX(8,M) contains the load line number of a prestressing element specified by Card Type VIIIa.

(Continue)

Card Type VI (Continued)

Continuum elements: IX(1,M), IX(2,M), IX(3,M) and IX(4,M) are displacement nodes. Element has only the 2 degrees of freedom per node option. Basically a quadrilateral shape. Triangular shape can be achieved by setting IX(4,M)=IX(3,M). Nodes describing element are connected counterclockwise. IX(5,M), IX(6,M), and IX(7,M) store the reinforcement ratios (multiplied by 10000) in the directions xi, eta, theta, respectively. IX(8,M) stores the angle (in degrees) of the xi-reinforcement with respect to the r-axis (xi, eta, theta are orthogonal axes of reinforcement).

Element cards which can be generated by adding INCR to all node numbers (those describing the element) of the previous element need not be included because they will be generated automatically. The last element card is needed however.

INCLUDE ONLY IF NUMDIS > 0 ON CARD TYPE II

Card Type VII   Prescribed Displacement Card (I10,E10.4)

```
1           7   9   11        16        21        26        31        36
+-----------+-+-+-+-+--------------------+---------------------------------------+
| N         | |I|I|I| ANGLE              |                                       |
+-----------+-+-+-+-+--------------------+---------------------------------------+

41        46        51        56        61        66        71        76
+--------------------------------------------------------------------------------+
|                                                                                |
+--------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-6	N	Node number at which one or more displacement components are specified. Essential boundary conditions/support conditions.
7		blank.
8	I	x-displacement component.
9	I	y-displacement component.
10	I	Blank for 2 degree of freedom nodes. Angular-displacement component for 3 degree of freedom nodes. I=0: displacement component has no constraint. I=1: displacement component is zero. I=2: displacement component is prescribed a value in subroutine FREEFD.
11-20	ANGLE	Angle of rotation (in degrees), right-hand rule, of the node before application of the constraint. Angle of rotation is used if a displacement component other than the x or y component prescribed. Do not rotate rotation nodes that are to be constrained for NDGREE=2.

For NDGREE=2 beam or shell element 'dummy' nodes, constrain both components whenever the node is to be constrained against rotation.

Internal incrementing by one is done between two prescribed displacement nodes by placing a minus sign in column preceding the last node number.

Use as many cards as there are nodes having prescribed displacements.

INCLUDE FOR ALL DATA SETS

Card Type VIIIa   Load Line Card (6I5,E10.4)

```
1         6         11        16        21        26        31        36
+---------+---------+---------+---------+---------+---------+-------------------+
| I       | NDNOD   | IVOL(1) | IVOL(2) | INT1    | NPT     | VINT              |
+---------+---------+---------+---------+---------+---------+-------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	I	Load line number.
6-10	NDNOD	Number of nodes* on load line.
11-15	IVOL(1)	External loading condition or property variation. IVOL(1)=0: initial velocity input. IVOL(1)=1: pressure-time (or increment) input. IVOL(1)=2: pressure-volume# input. IVOL(1)=3: force-time input (x-component). IVOL(1)=4: force-time input (y-component). IVOL(1)=5: displacement-time input (x-component). IVOL(1)=6: displacement-time input (y-component). IVOL(1)=7: temperature-time input. IVOL(1)=8: heat flux-time input. IVOL(1)=9: film coefficient-time input. IVOL(1)=10: internal heat source-time input. IVOL(1)=11: prestressing-time input.$
16-20	IVOL(2)	Geometry of external loading. IVOL(2)=0: plane geometry (all elements). IVOL(2)=1: axisymmetric geometry (velocity-strain concrete or continuum element, 1 point Gaussian). IVOL(2)=2: axisymmetric geometry (velocity-strain concrete or continuum element, 2 point Gaussian). IVOL(2)=3: axisymmetric geometry (shell element).
21-25	INT1	Node interval: if the node numbers of a load line can be generated by adding INT1 each time, read in INT1 and skip all node data but the first node on Card Type VIIIc, otherwise INT1=0 or blank.

(Continue)

Card Type VIIIa (Continued)

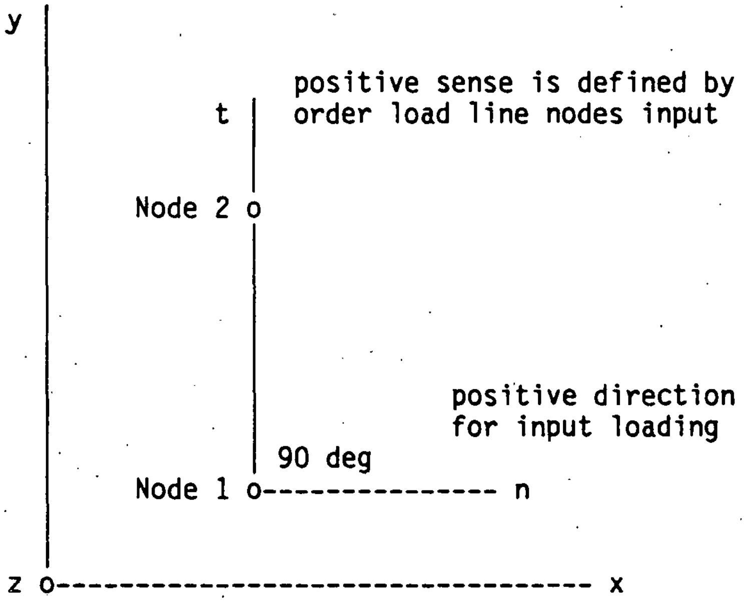
Columns	Variable	Description
26-30	NPT	Number of points used to define the piecewise linear function for pressure, force, displacement or thermal input on Card Type VIIIb-1 if not using IVOL(1)=0.
31-40	VINT	Initial volume of load line if using IVOL(1)=2. Angle of heat flux to x-axis if using IVOL(1)=8. Far field fluid temperature if using IVOL(1)=9.

*Number of elements on load line if using IVOL(1)=10 or 11.

#Volume is volume change divided by initial volume.

$This loading condition is applied prior to the desired simulation.

See following figure indicating positive direction for input loading.



The positive direction for the impulse, pressure or thermal input of the load line is defined by rotating clockwise 90 degrees from the positive sense of the load line. The positive sense of the load line is defined by the order in which the node numbers are read as input.

INCLUDE ONLY IF IVOL(1) > 0 ON CARD TYPE VIIIa

Card Type VIIIb-1   Load Line Card (8E10.4)

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| PT(1)             | PT(2)             | PT(3)             | PT(4)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------+-------------------+
| PT(5)             | PT(6)             | PT(7)             | PT(8)             |
+-------------------+-------------------+-------------------+-------------------+
```

Columns	Variable	Description
1-10	PT(1)	Time, point 1.
11-20	PT(2)	Pressure,* point 1.
21-30	PT(3)	Time, point 2.
31-40	PT(4)	Pressure, point 2.
41-50	PT(5)	Time, point 3.
51-60	PT(6)	Pressure, point 3.
61-70	PT(7)	Time, point 4.
71-80	PT(8)	Pressure, point 4.

If p(0)=0.0, then (0,0) need not be input.

If less than three points desired, leave the field blank.

Additional Type VIIIb-1 cards may be used if more points are desired to describe the load line input. No limit on number of points.

*The sign convention is stated on Card Type VIIIa.

INCLUDE ONLY IF IVOL(1) = 0 ON CARD TYPE VIIIa

Card Type VIIIb-2   Load Line Card (4E10.4)

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+-------------------+-------------------+
| PT(1)             | PT(2)             | PT(3)             | PT(4)             |
+-------------------+-------------------+-------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	PT(1)	Prescribed component of velocity* at time=0, tangent to load line.
11-20	PT(2)	Prescribed component of velocity at time=0, normal to load line.
21-30	PT(3)	First node factor. Factor by which impulse is multiplied at first node on load line (should be 2.0 if first node is on line of symmetry). If left blank, impulse at first node is not changed.
31-40	PT(4)	Last node factor. Same condition as above.

*The sign convention is stated on Card Type VIIIa.

INCLUDE FOR ALL DATA SETS

Card Type VIIIc   Load Line Card (16I5)

```
1         6         11        16        21        26        31        36
+---------+---------+---------+---------+---------+-----------------------------+
| KPR(1)  | KPR(2)  | KPR(3)  | KPR(4)  | etc.    |                             |
+---------+---------+---------+---------+---------+-----------------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	KPRES(1)	Nodes* on load line.
6-10	KPRES(2)	

etc.

If all nodes can be generated for KPRES(J), J=2 to NDNOD, by incrementing by INT1, only KPRES(1) need be included.

Additional Type VIIIc cards may be used if this card is inadequate to describe all the nodes on the load line.

*When using temperature-, heat flux- and film coefficient-time (or increment) input the nodes on the load line are those associated with the thermal mesh. When using internal heat source-time input the thermal elements are input to the load line instead of nodes. Structural mesh bar and ring elements are input to the load line instead of nodes when using prestressing-time input.

INCLUDE ONLY IF NSLID > 0 ON CARD TYPE II

Card Type IXa Sliding/Rigid Interface Card (6I5,3E10.2)

```
1         6         11        16        21        26        31        36
+---------+---------+---------+---------+---------+---------+-----------------+
| M       | ND1     | ND2     | INT1    | INT2    | NRM     | SLIPAR(1)       |
+---------+---------+---------+---------+---------+---------+-----------------+

41        46        51        56        61        66        71        76
+-------------------+-------------------+-------------------------------------+
| SLIPAR(2)         | SLIPAR(3)         |                                     |
+-------------------+-------------------+-------------------------------------+
```

Columns	Variable	Description
1-5	M	Sliding/rigid interface number.
6-10	ND1	Number of master nodes* for interface.
11-15	ND2	Number of slave nodes* for interface.
16-20	INT1	Automatic generator for the nodes on master side. If INT1>0, only first node on master side need be input.
21-25	INT2	Automatic generator for the nodes on slave side. If INT2>0, only first node on slave side need be input.
26-30	NRM	Sliding/rigid mode option. NRM=0: sliding interface. NRM=1: rigid continuum interface. NRM=2: rigid flexural interface. NRM=3: flexural offset rigid interface.
31-40	SLIPAR(1)	Coulomb friction: static friction coefficient. Viscous friction: dynamic viscosity coefficient.
41-50	SLIPAR(2)	Coulomb friction: dynamic friction coefficient. Viscous friction: boundary layer thickness.
51-60	SLIPAR(3)	Coulomb friction: SLIPAR(3)=0.0. Viscous friction: SLIPAR(3)=1.0.

*On lines of symmetry and for most cases involving boundary/support nodes, nodes should not exist for sliding interfaces. For rigid interfaces, only the translational nodes are necessary for nodal input data. The rotational nodes are generated internally for those elements with flexural resistance.

INCLUDE ONLY IF NSLID > 0 ON CARD TYPE II

Card Type IXb Sliding/Rigid Interface Card (16I5)

```
1         6         11        16        21        26        31        36
+---------+---------+---------+---------+---------+-----------------------------+
| KS(1,1) | KS(1,2) | KS(1,3) | KS(1,4) | etc.    |                             |
+---------+---------+---------+---------+---------+-----------------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

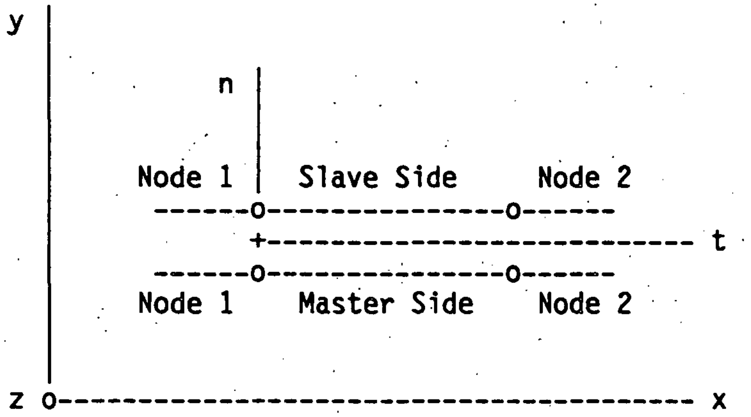
Columns	Variable	Description
1-5	KSLID(1,1)	First node on master side of interface.
6-10	KSLID(1,2)	Second node on master side of interface.

etc.

If all nodes can be generated for KSLID(1,J), J=2 to ND1, by incrementing by INT1, only KSLID(1,1) need be included.

Additional Type IXb cards may be used if this card is inadequate to describe all the nodes on the load line.

See following figure describing sliding interface pairs.



Each node pair must have the same coordinate values. KSLID(1,J) to KSLID(2,J) defines the n-local direction; t-local is normal to n and defined by the order in which the node numbers are read as input. At corners, t is the tangent average.

See the theory manual for a description of rigid interface master-slave nodes.

INCLUDE ONLY IF NSLID > 0 ON CARD TYPE II

Card Type IXc   Sliding/Rigid Interface Card (16I5)

```
1         6         11        16        21        26        31        36
+---------+---------+---------+---------+---------+----------------------------+
| KS(2,1) | KS(2,2) | KS(2,3) | KS(2,4) | etc.    |                            |
+---------+---------+---------+---------+---------+----------------------------+

41        46        51        56        61        66        71        76
+------------------------------------------------------------------------------+
|                                                                              |
+------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-5	KSLID(2,1)	First node on slave side of interface.
6-10	KSLID(2,2)	Second node on slave side of interface.
etc.		

If all nodes can be generated for KSLID(2,J), J=2 to ND2, by incrementing by INT2, only KSLID(1,1) need be included.

Additional Type IXc cards may be used if this card is inadequate to describe all the nodes on the load line.

INCLUDE FOR ALL DATA SETS

Card Type Xa   Output Card (4I10)

```
1       6       11      16      21      26      31      36
+----------------+----------------+----------------+----------------+
| NPFREQ         | NPRU           | NPRS           | NPIC           |
+----------------+----------------+----------------+----------------+

41      46      51      56      61      66      71      76
+-------------------------------------------------------------------+
|                                                                   |
+-------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	NPFREQ	Frequency of output. Whatever output is desired will be printed every NPFREQ step.
11-20	NPRU	Number of motion* output records.
21-30	NPRS	Number of element# output records.
31-40	NPIC	Number of complete (different motion and/or element records at a particular time step for all nodes and/or elements) output pictures.

*A motion record is a single displacement, velocity, acceleration, external force or internal force component of a node.

#An element record here means a single strain or stress component of an element; a volume change of a pressure line; an external loading; or one of several energy calculations.

INCLUDE ONLY IF NPRU > 0 ON CARD TYPE Xa

Card Type Xb   Motion Output Card (I10,5A4,2E10.4)

```
1          7 9  11        16        21        26        31        36
+-----------+-+-+-+-+---------------------------------------+-------------------+
| N         | |J|K|L| Alphanumeric                          |                   |
+-----------+-+-+-+-+---------------------------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+-----------------------------------------------------------+
|                   |                                                           |
+-------------------+-----------------------------------------------------------+
```

Columns	Variable	Description
1-6	N	Node number.
7		blank.
8	J	Component number. J=1: x-component. J=2: y-component. J=3: rotation component.
9	K	Motion record flag. K=0: displacement record. K=1: velocity record. K=2: acceleration record. K=3: external force record. K=4: internal force record.
10	L	Output type flag. L=0: printed values of motion record. L=1: printed values, printer plot and graphics plot of motion record. L=2: printed values, printer plot and punched cards of motion record. L=3: printed values, printer plot, graphics plot, and punched cards of motion record. L=4: printed values and printer plot of motion record.
11-30		Alphanumeric information to be written on ordinate axis and above the graphics plot.

Include the following if automatic scaling is to be overridden for graphics plot.

31-40		Scale of ordinate value per inch of plot.
41-50		Minimum value of ordinate.

INCLUDE ONLY IF NPRS > 0 ON CARD TYPE Xa

Card Type Xc   Element Output Card (I10,5A4,2E10.4)

```
1           7     10 11        16        21        26        31        36
+-----------+-----+-+----------------------------------------+-------------------+
| M         | J   |L| Alphanumeric                           |                   |
+-----------+-----+-+----------------------------------------+-------------------+

41        46        51        56        61        66        71        76
+-------------------+------------------------------------------------------------+
|                   |                                                            |
+-------------------+------------------------------------------------------------+
```

Columns	Variable	Description
1-6	M	Element number.
7-9	J	Component number (see following pages).
10	L	Output type flag. L=0: printed values of element record. L=1: printed values, printer plot and graphics plot of element record. L=2: printed values, printer plot and punched cards of element record. L=3: printed values, printer plot, graphics plot, and punched cards of element record. L=4: printed values and printer plot of motion record.
11-30		Alphanumeric information to be written on ordinate axis and above the graphics plot.

Include the following if automatic scaling is to be overridden for graphics plot.

31-40		Scale of ordinate value per inch of plot.
41-50		Minimum value of ordinate.

(Continue)

Card Type Xc (Continued)

Beam or Shell Element Component Numbers - J

J-values for element component	at length point 1 for thickness points 1 to NPD	at length point NPL for thickness points NP-NPD+1 to NP
eps-x,mech	1 to NPD	NP-NPD+1 to NP
sig-x	NP+1 to NP+NPD	2*NP-NPD+1 to 2*NP
sig-yield	2*NP+1 to 2*NP+NPD	3*NP-NPD+1 to 3*NP
temperature	3*NP+1 to 3*NP+NPD	4*NP-NPD+1 to 4*NP
eps-z,mech	4*NP+1 to 4*NP+NPD	5*NP-NPD+1 to 5*NP
sig-z	5*NP+1 to 5*NP+NPD	6*NP-NPD+1 to 6*NP
eps-e,plas	6*NP+1 to 6*NP+NPD	7*NP-NPD+1 to 7*NP
eps-x,plas	7*NP+1 to 7*NP+NPD	8*NP-NPD+1 to 8*NP
eps-z,plas	8*NP+1 to 8*NP+NPD	9*NP-NPD+1 to 9*NP
temperature*	9*NP+1 to 9*NP+NPD	10*NP-NPD+1 to 10*NP

NPL - number of integration points along element length, specified in E(15) on material property Card Type IVb-1 or IVb-11.

NPD - number of integration points through element thickness, specified in E(16) on material property Card Type IVb-1 or IVb-11.

NP = NPL*NPD - total number of integration points.

*The shell element also has thermal node temperatures.

See following figure (local x, y, z coordinates) for location of components.

(Continue)

Card Type Xc (Continued)

```
        y |
          |
          |
          |
Point NPD +-----------------------------------------------+ Point NP
          |                                               |
          |                                               |
          | Node 1                                 Node 2 |
        z o-----------------------------------------------o--------- x
          |                                               |
          |                                               |
          |                                               |
Point 1   +-----------------------------------------------+ Point NP-NPD+1
```

x coordinate direction is determined by vector from Node 1 to Node 2 while y is determined by right-hand rule for indicating location of component numbers. The beam element uses the element interface locations for length integration points with thickness integration points being at equal intervals. The shell element uses Gaussian integration points along the length (usually 2) and through the thickness.

(Continue)

Card Type Xc (Continued)

Plane or Axisymmetric Continuum Element Component Numbers - J

J-values for element component	at Gaussian point 1	at Gaussian point NP
eps-x,mech	1	25*(NP-1)+1
eps-y,mech	2	25*(NP-1)+2
eps-xy,mech	3	25*(NP-1)+3
eps-z,mech	4	25*(NP-1)+4
sig-x	5	25*(NP-1)+5
sig-y	6	25*(NP-1)+6
sig-xy	7	25*(NP-1)+7
sig-z	8	25*(NP-1)+8
eps-x,plas	9	25*(NP-1)+9
eps-y,plas	10	25*(NP-1)+10
eps-xy,plas	11	25*(NP-1)+11
eps-z,plas	12	25*(NP-1)+12
eps-e,plas	13	25*(NP-1)+13
sig-yield	14	25*(NP-1)+14
temperature	15	25*(NP-1)+15

J-values for element component	at Node 1	at Node 2	at Node 3	at Node 4
temperature	22	23	24	25

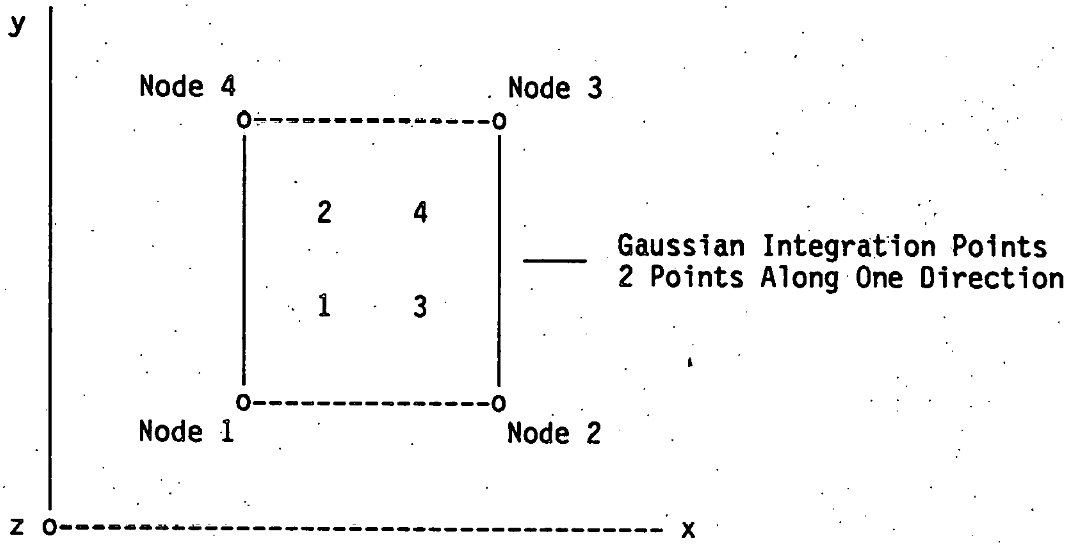
(Continue)

Card Type Xc (Continued)

NP - Gaussian integration point of element selected for output, maximum point would be NGP*NGP.

NGP - number of Gaussian integration points along one direction, specified in E(16) on material property Card Type IVb-2 or IVb-12.

See following figure (global x, y, z coordinates) for location of components.



Output for the quadrilateral continuum element is given at the Gaussian integration points in the global coordinate system x, y, z. Shown here is the location of the integration stations for 2 Gaussian integration points along one direction.

(Continue)

Card Type Xc (Continued)

Plane or Axisymmetric Concrete Element Component Numbers - J

J-values for element component	at Gaussian point 1	at Gaussian point NP
eps-x,mech	1	NHV*(NP-1)+1
eps-y,mech	2	NHV*(NP-1)+2
eps-xy,mech	3	NHV*(NP-1)+3
eps-z,mech	4	NHV*(NP-1)+4
sig-x	5	NHV*(NP-1)+5
sig-y	6	NHV*(NP-1)+6
sig-xy	7	NHV*(NP-1)+7
sig-z	8	NHV*(NP-1)+8
eps-x,plas	9	NHV*(NP-1)+9
eps-y,plas	10	NHV*(NP-1)+10
eps-xy,plas	11	NHV*(NP-1)+11
eps-z,plas	12	NHV*(NP-1)+12
eps-e,plas	13	NHV*(NP-1)+13
sig-yield	14	NHV*(NP-1)+14
temperature	15	NHV*(NP-1)+15

J-values for element component	at Node 1	at Node 2	at Node 3	at Node 4
temperature	22	23	24	25

(Continue)

Card Type Xc (Continued)

J-values for element component	at Gaussian point 1	at Gaussian point NP
crack ang1	30	NHV*(NP-1)+30
crack ang2	31	NHV*(NP-1)+31
crack type	32	NHV*(NP-1)+32
id-plas	33	NHV*(NP-1)+33

J-values for element (rbar) component	available only if one point
sig-xi	34
sig-eta	35
sig-theta	36
yield-xi	37
yield-eta	38
yield-theta	39

NGP - number of Gaussian integration points along one direction, specified in E(16) on material property Card Type IVb-3 or IVb-13.

NP - Gaussian integration point of element selected for output, maximum point would be NGP*NGP.

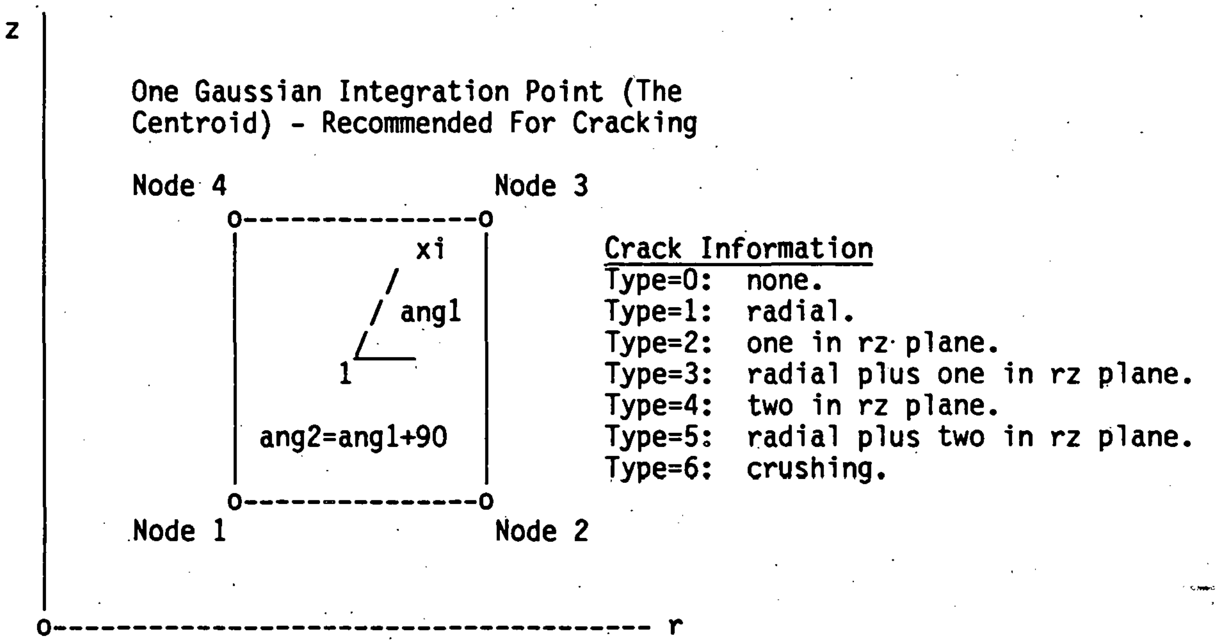
NHV = 48 - plane concrete element output values per integration point.

NHV = 51 - axisymmetric concrete element output values per integration point.

See following figure (global cylindrical coordinates) for location of components and crack output information.

(Continue)

Card Type Xc (Continued)



Crack Information

Type=0: none.
Type=1: radial.
Type=2: one in rz plane.
Type=3: radial plus one in rz plane.
Type=4: two in rz plane.
Type=5: radial plus two in rz plane.
Type=6: crushing.

Output for the quadrilateral concrete element is given at the Gaussian integration points in global cylindrical coordinates. Shown here is the location of the integration station for one Gaussian integration point (the element centroid). For cracking, if using a global x, y, z coordinate system, the rz plane becomes the xy plane with an existing radial crack. Then, only Type=1, 3, 5 and 6 exist.

Card Type Xc (Continued)

Concrete Beam or Shell Element Component Numbers - J

J-values for element component	at length point 1 for thickness points 1 to NPD	- - -	at length point NPL for thickness points NP-NPD+1 to NP
eps-x,mech	1 to NPD		NP-NPD+1 to NP
sig-x	NP+1 to NP+NPD		2*NP-NPD+1 to 2*NP
sig-yield	2*NP+1 to 2*NP+NPD		3*NP-NPD+1 to 3*NP
temperature	3*NP+1 to 3*NP+NPD		4*NP-NPD+1 to 4*NP
eps-z,mech	4*NP+1 to 4*NP+NPD		5*NP-NPD+1 to 5*NP
sig-z	5*NP+1 to 5*NP+NPD		6*NP-NPD+1 to 6*NP
eps-e,plas	6*NP+1 to 6*NP+NPD		7*NP-NPD+1 to 7*NP
eps-x,plas	7*NP+1 to 7*NP+NPD		8*NP-NPD+1 to 8*NP
eps-z,plas	8*NP+1 to 8*NP+NPD		9*NP-NPD+1 to 9*NP
temperature*	9*NP+1 to 9*NP+NPD		10*NP-NPD+1 to 10*NP
alpha-x	10*NP+1 to 10*NP+NPD		11*NP-NPD+1 to 11*NP
alpha-z	11*NP+1 to 11*NP+NPD		12*NP-NPD+1 to 12*NP
icrack	12*NP+1 to 12*NP+NPD		13*NP-NPD+1 to 13*NP
id-plas	13*NP+1 to 13*NP+NPD		14*NP-NPD+1 to 14*NP
eps-rbar	NL+1 to NL+NRB		NL+MP-NRB+1 to NL+MP
sig-rbar	NL+MP+1 to NL+MP+NRB		NL+2*MP-NRB+1 to NL+2*MP
yield-rbar	NL+2*MP+1 to NL+2*MP+NRB	- - -	NL+3*MP-NRB+1 to NL+3*MP

NPL = 2 - number of integration points along element length.

NPD - number of integration points through element thickness, specified in E(16) on material property Card Type IVb-4 or IVb-14.

NP = 2*NPD - total number of integration points.

(Continue)

Card Type Xc (Continued)

NL = 17*NP - beam concrete element output values without reinforcement.

NL = 20*NP - shell concrete element output values without reinforcement.

NRB - number of reinforcing layers.

MP = 2*NRB

*The shell element also has thermal node temperatures.

See following figure (local x, y, z coordinates) for location of components.

```
        y |
          |
          |
          |
Point NPD +-----------------------------------------------+ Point NP
          |                                               |
          |             Reinforcement layer 3             |
          |- - - - - - - - - - - - - - - - - - - - - - - -|- - *
          |                                               |    y3
          | Node 1                                 Node 2 |    |
        z o-----------------------------------------------o----*----*---- x
          |             Reinforcement layer 2             |   -y2  |
          |- - - - - - - - - - - - - - - - - - - - - - - -|- - *   -y1
          |             Reinforcement layer 1             |         |
          |- - - - - - - - - - - - - - - - - - - - - - - -|- - - - -*
          |                                               |
Point 1   +-----------------------------------------------+ Point NP-NPD+1
```

x coordinate direction is determined by vector from Node 1 to Node 2 while y is determined by right-hand rule for indicating location of component numbers. The beam element uses the element interface locations for length integration points with thickness integration points being at equal intervals. The shell element uses Gaussian integration points along the length (usually 2) and through the thickness.

(Continue)

Card Type Xc (Continued)

In addition, these values can be obtained:

Special Element Associated Values	Element Number	J-Values
Volume change of load line	M=NUMEL*+1	J=load line number.
External loading	M=NUMEL+2	J=load line number.
Internal energy of material	M=NUMEL+3	J=material type number.
External energy of load line	M=NUMEL+4	J=load line number.
Kinetic energy	M=NUMEL+5	J=1
Total internal energy	M=NUMEL+5	J=2
Total external energy	M=NUMEL+5	J=3
Total energy	M=NUMEL+5	J=4
Energy error, $\frac{\text{total ext - total}}{\text{total ext}}$	M=NUMEL+5	J=5
Estimated period of first mode associated with dynamic relaxation	M=NUMEL+5	J=6

*NUMEL = number of elements defined on Card Type II.

INCLUDE ONLY IF NPIC > 0 ON CARD TYPE Xa

Card Type Xd   Picture Output Card (2I10)

```
1         6         11        16        21        26        31        36
+-------------------+-------------------+---------------------------------------+
| NTSTEP            | K                 |                                       |
+-------------------+-------------------+---------------------------------------+

41        46        51        56        61        66        71        76
+-------------------------------------------------------------------------------+
|                                                                               |
+-------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	NTSTEP	Time step or load increment at which complete global output is desired.
11-20	K	Output type flag. K=0: graphics plot only. K=1: output displacements at all nodes. K=2: output from K=1 plus coordinates of deformed structure (for NDGREE=2, output for rotational nodes is same as K=1). K=3: output from K=2 plus velocities and accelerations at all nodes. K=4: output from K=3 plus strains and stresses for all elements.

Deformed graphics plots of the mesh may be obtained at the various time steps for K=2, 3, or 4 by requesting a mesh plot on Card Type III.

INCLUDE ONLY IF KONTRL(6) = 1 ON CARD TYPE III

Card Type XI   Gravity Loading Card (3E10.4)

```
1         6         11        16        21        26        31        36
+--------------------+--------------------+--------------------+--------------------+
| ACCG               | CXX                | CYY                |                    |
+--------------------+--------------------+--------------------+--------------------+

41        46        51        56        61        66        71        76
+-----------------------------------------------------------------------------------+
|                                                                                   |
+-----------------------------------------------------------------------------------+
```

Columns	Variable	Description
1-10	ACCG	Acceleration of gravity rate.
11-20	CXX	x-direction cosine for gravity.
21-30	CYY	y-direction cosine for gravity.

4. Sample Problems

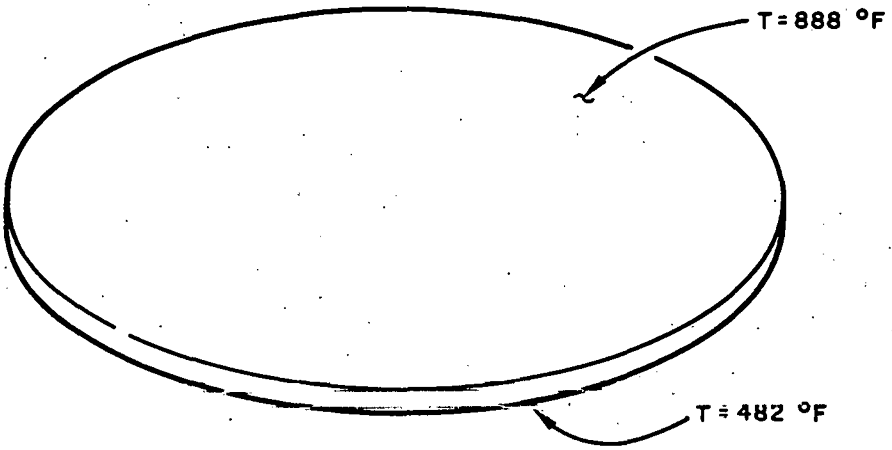
4.1 Sample Problem 1: Thermally Loaded Axisymmetric Plate

Problem 1, shown in Fig. 4.1, is a tungsten axisymmetric plate whose upper surface is heated from an initial temperature of 482°F to 888°F. The bottom surface of the plate is prescribed to remain at 482°F. The thermal distribution occurs only through the plate. At the outer edge of the plate, the plate is assumed to be displacement restricted in the normal direction. Also shown in Fig. 4.1 is the 10 shell element stress mesh and the 60 rectangular element thermal mesh. The material properties and parameters needed for modeling are provided in Table 4.1; the material properties will remain constant over the temperature range. Table 4.2 provides the input data for the problem. The temperature distribution through the plate thickness is given in Fig. 4.2 for the analytical and theoretical cases. A very good agreement is achieved for this coarse discretization.

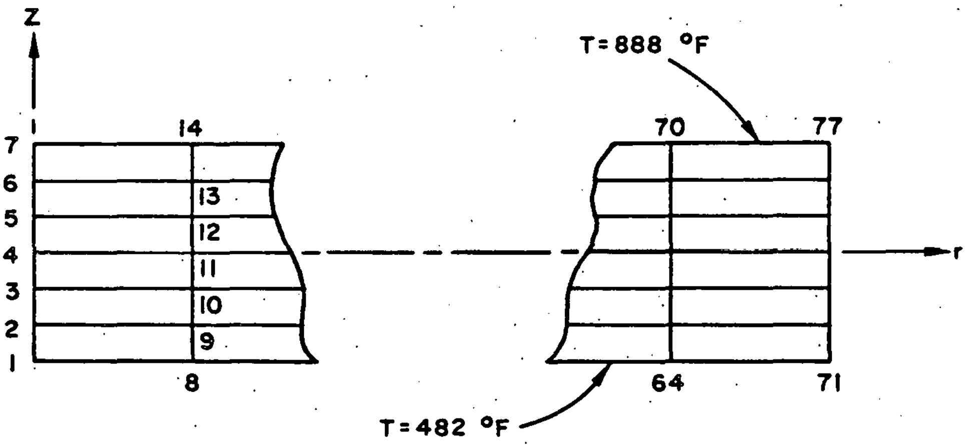
Table 4.1 Material Properties and Parameters for Axisymmetric Plate (Sample Problem 1)

Radius	$r = 10.0$ in
Thickness	$t = 0.25$ in
Density	$\rho = 1.806 \times 10^{-3}$ lb-sec^2/in^4
Young's modulus	$E = 5.2 \times 10^7$ psi
Poisson's ratio	$\nu = 0.25$
Yield stress	$\sigma_Y = 7.5 \times 10^4$ psi
Plastic modulus	$E_p = 1.0 \times 10^5$ psi
Thermal expansion coefficient	$\alpha = 5.17 \times 10^{-6}$ in/in/°F
Thermal conductivity	$k = 5.29 \times 10^{-4}$ btu/sec/in/°F
Specific heat	$c = 5.537$ btu/lb/sec^2/in/°F

(a)



(b) THERMAL MESH



(c) STRESS MESH

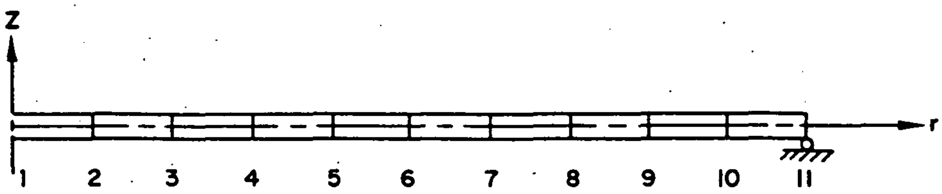


Figure 4.1 Thermal Loading and Finite Element Models for Axisymmetric Plate

Table 4.2 Input Cards for Sample Problem 1

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1  PLATE PROBLEM - 10 STRESS ELEMENTS - 6 THERMAL ELEMENTS PER STRESS ELEMENT        Card I
 2     11   10    1    2   16    3     0.125    1                                     Card II
 3      2    0             90                               2000  100   10            Card III
 4      1   11TUNGSTEN                                                                Card IVa-11
 5    1.806E-3                0.25   5.17E-6  0.000529  5.537099       1.0       2.0  Card IVb-11
 6                     1.0       0.0       0.0       0.0       3.0       2.0       7.0  Card IVc-11
 7       482.0   52.0E+6 0.0014423   75000.0 0.5014423  125000.0                      Card IVd-11
 8      1            0.0       0.0                                                    Card V
 9     11           10.0       0.0                                                    Card V
10      1    1    2    0    0    0    0    0    0    1   11                           Card VI
11     10   10   11    0    0    0    0    0    0    1   11                           Card VI
12       10101                                                                        Card VII
13      110010                                                                        Card VII
14      1   11    7    3    7    3                                                    Card VIIIa
15         0.0     482.0       2.0     888.0      50.0     888.0                      Card VIIIb-1
16      7                                                                             Card VIIIc
17           1         2         9         1                                          Card Xa
18       10204Z-DISP NODE 1                                                           Card Xb
19      110104R-DISP NODE 11                                                          Card Xb
20       10014EMX AT STA 1 ELE 1                                                      Card Xc
21       10074EMX AT STA 7 ELE 1                                                      Card Xc
22       10154STX AT STA 1 ELE 1                                                      Card Xc
23       10214STX AT STA 7 ELE 1                                                      Card Xc
24       10434TEM AT STA 1 ELE 1                                                      Card Xc
25       10464TEM AT STA 4 ELE 1                                                      Card Xc
26       10494TEM AT STA 7 ELE 1                                                      Card Xc
27      120014APPLIED TEMPERATURE                                                     Card Xc
28      130014INTERNAL ENERGY                                                         Card Xc
29          16         4                                                              Card Xd
```

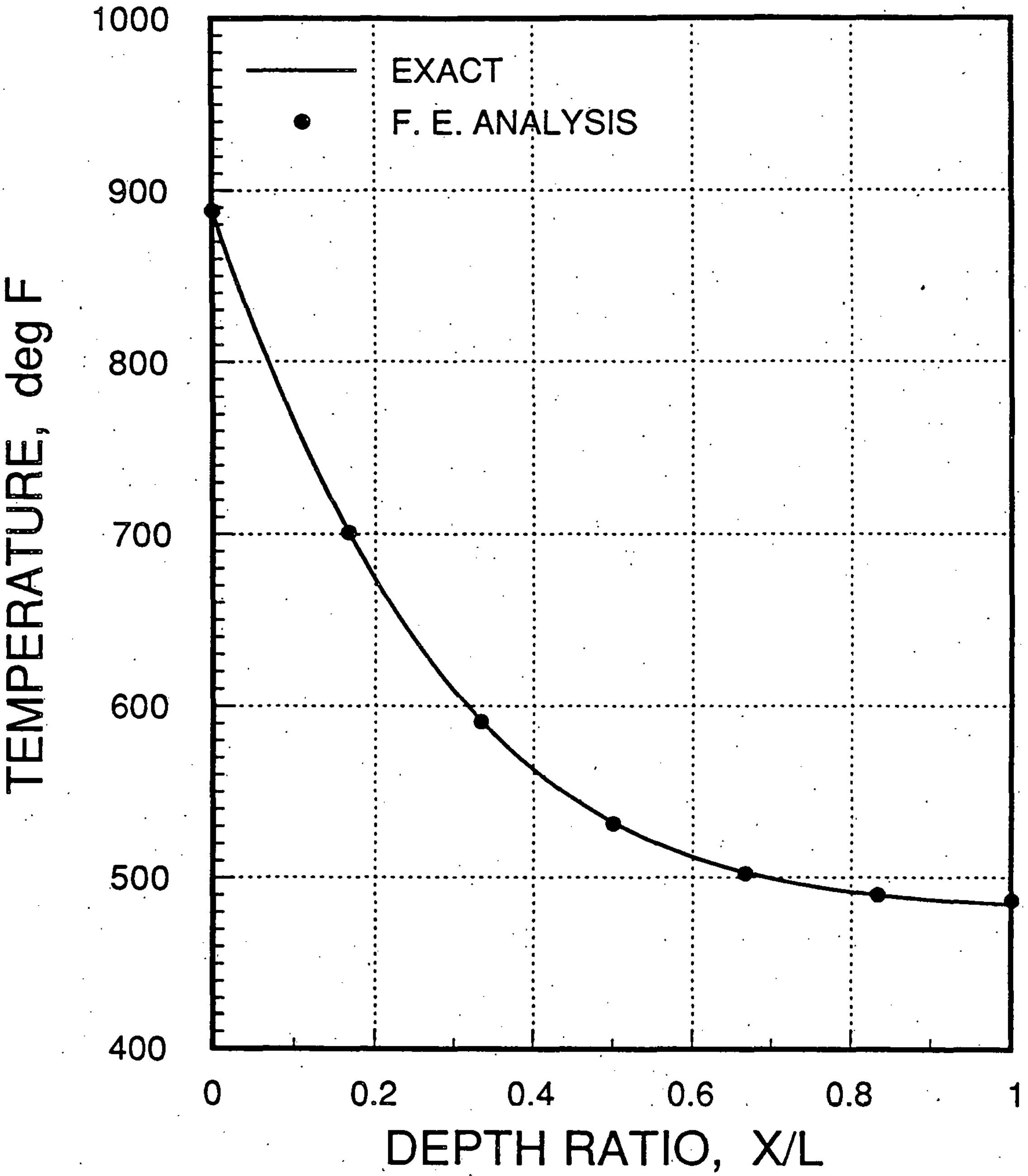


Figure 4.2 Temperature Distribution Through the Plate Thickness

4.2 Sample Problem 2: Thermal Analysis of Rectangular Plate

The analytical results of a rectangular plate problem described by plane quadrilateral continuum elements for a two-dimensional temperature field can be compared with the theoretical solution. Here, a sinusoidal temperature distribution is prescribed at one side, and zero temperature on the remaining sides. The theoretical steady-state temperature distribution along the line of symmetry is shown in Fig. 4.3. This figure also shows the analytical result, where the model uses one-half of the plate area. Four meshes were used to model this problem: 2 x 4 elements, 3 x 6 elements, 4 x 8 elements and 5 x 10 elements. A plot of contour isotherms for the four models are shown in Fig. 4.4. The case of 2 x 4 elements in the analytical model provides maximum deviation from the theoretical predictions, and the finer mesh models provide closer agreement. The overall agreement, however, appears very good. The input cards for the 50 element mesh are given in Table 4.4.

Table 4.3 Material Properties and Parameters for Rectangular Plate (Sample Problem 2)

Length	$L = 4.0$ cm
Thickness	$t = 1.0$ cm
Density	$\rho = 1.0$ g/cm^3
Young's modulus	$E = 1.0 \times 10^{10}$ dynes/cm
Poisson's ratio	$\nu = 0.3$
Thermal expansion coefficient	$\alpha = 2.0 \times 10^{-5}$ cm/cm/°C
Thermal conductivity	$k = 1.0$ cal/sec/cm/°C
Specific heat	$c = 1.0$ cal/g/°C

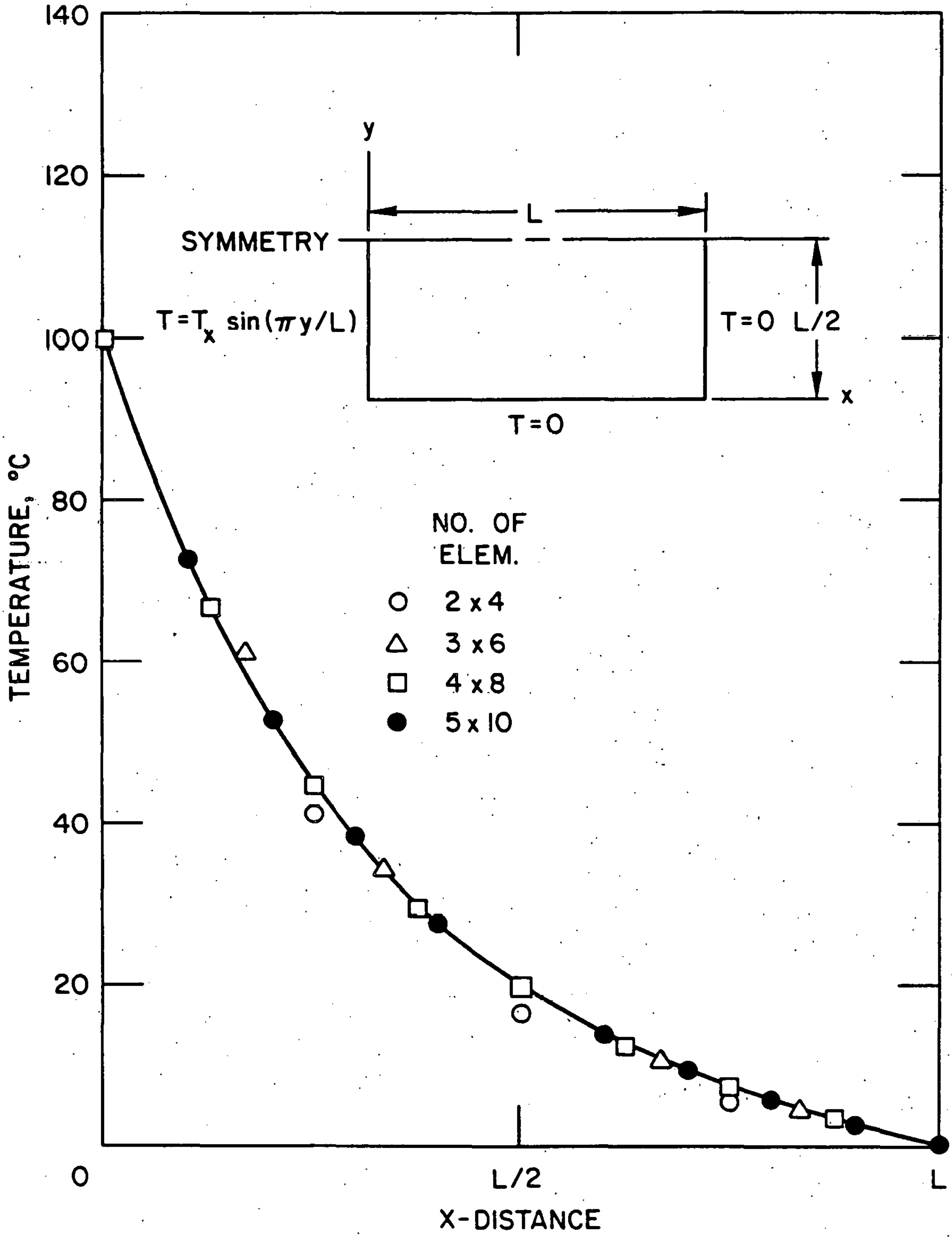
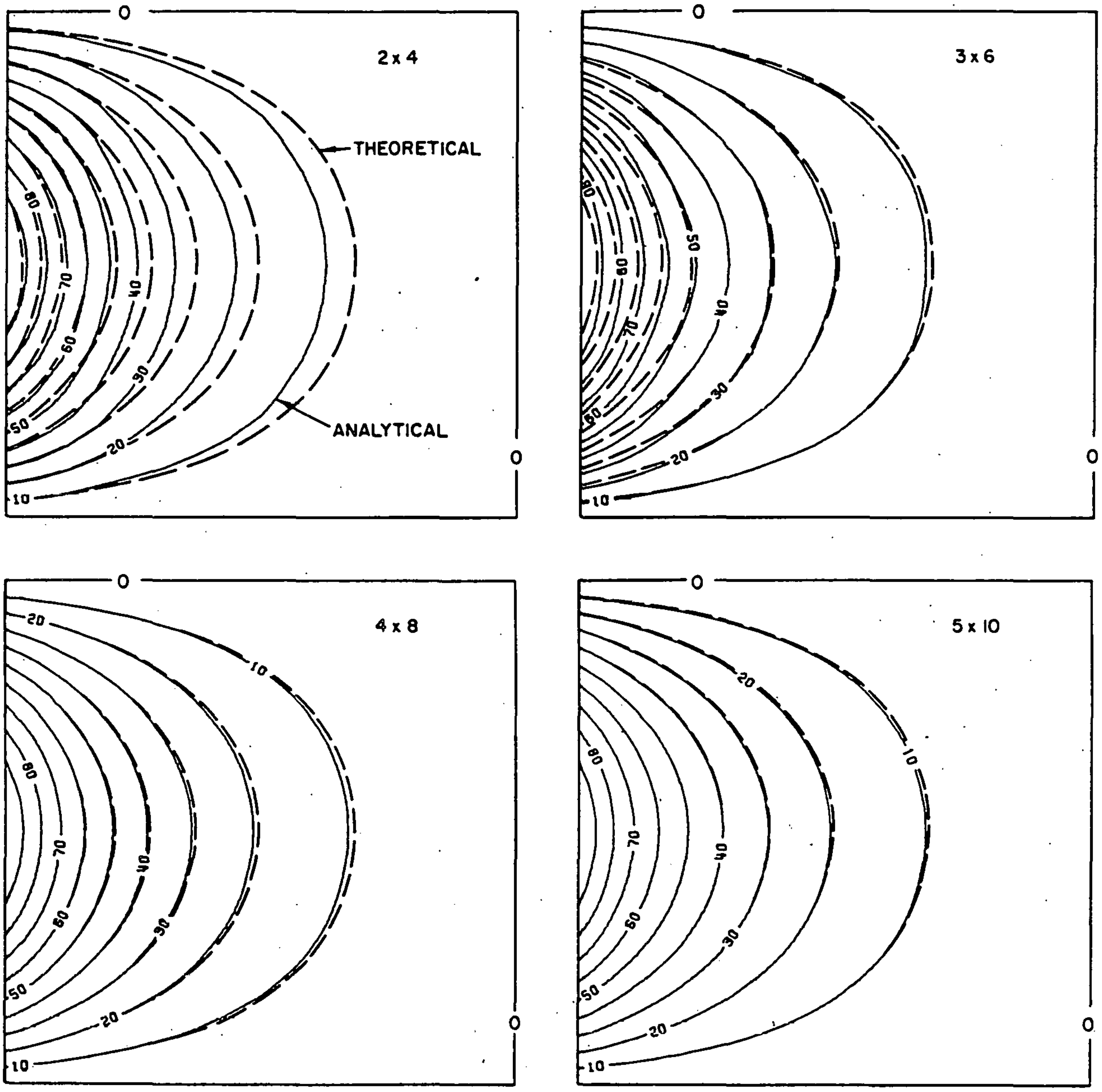


Figure 4.3 Temperature Variation Along the Line of Symmetry


2 x 4

3 x 6

4 x 8

5 x 10

Figure 4.4 Contour Plots of Temperature Distribution

Table 4.4 Input Cards for Sample Problem 2

```
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
  1  50 ELEMENT MODEL OF RECTANGULAR PLATE - THERMAL ANALYSIS                          Card I
  2     66   50    1    2  130    2    5.0E-2    7                                     Card II
  3      2    0            90                               2000  100   10            Card III
  4      1    2                                                                        Card IVa-2
  5        1.0                 0.3    2.0E-5       1.0       1.0       1.0       2.0  Card IVb-2
  6        1.0       0.0       0.0       0.0       0.0      11.0                 2.0  Card IVc-2
  7        0.0    1.0E10       0.1     1.0E9       1.0     2.0E9                      Card IVd-2
  8      1            0.0       0.0                                                    Card V
  9      6            0.0       2.0                                                    Card V
 10      7            0.4       0.0                                                    Card V
 11     12            0.4       2.0                                                    Card V
 12     13            0.8       0.0                                                    Card V
 13     18            0.8       2.0                                                    Card V
 14     19            1.2       0.0                                                    Card V
 15     24            1.2       2.0                                                    Card V
 16     25            1.6       0.0                                                    Card V
 17     30            1.6       2.0                                                    Card V
 18     31            2.0       0.0                                                    Card V
 19     36            2.0       2.0                                                    Card V
 20     37            2.4       0.0                                                    Card V
 21     42            2.4       2.0                                                    Card V
 22     43            2.8       0.0                                                    Card V
 23     48            2.8       2.0                                                    Card V
 24     49            3.2       0.0                                                    Card V
 25     54            3.2       2.0                                                    Card V
 26     55            3.6       0.0                                                    Card V
 27     60            3.6       2.0                                                    Card V
 28     61            4.0       0.0                                                    Card V
 29     66            4.0       2.0                                                    Card V
 30      1    1    7    8    2                        1    2    6                      Card VI
 31     11    2    8    9    3                        1    2    6                      Card VI
 32     21    3    9   10    4                        1    2    6                      Card VI
 33     31    4   10   11    5                        1    2    6                      Card VI
 34     41    5   11   12    6                        1    2    6                      Card VI
 35     50   59   65   66   60                        1    2    6                      Card VI
```

Table 4.4 Input Cards for Sample Problem 2 (cont.)

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
36       60010                                                                          Card VII
37      660111                                                                          Card VII
38      1    1    7    0    0    2                                                    Card VIIIa
39         2.0      30.9      20.0      30.9                                          Card VIIIb-1
40      2                                                                               Card VIIIc
41      2    1    7    0    0    2                                                    Card VIIIa
42         2.0     58.78      20.0     58.78                                          Card VIIIb-1
43      3                                                                               Card VIIIc
44      3    1    7    0    0    2                                                    Card VIIIa
45         2.0      80.9      20.0      80.9                                          Card VIIIb-1
46      4                                                                               Card VIIIc
47      4    1    7    0    0    2                                                    Card VIIIa
48         2.0     95.11      20.0     95.11                                          Card VIIIb-1
49      5                                                                               Card VIIIc
50      5    1    7    0    0    2                                                    Card VIIIa
51         2.0     100.0      20.0     100.0                                          Card VIIIb-1
52      6                                                                               Card VIIIc
53      6   16    7    0    0    2                                                    Card VIIIa
54         0.0       0.0      20.0       0.0                                          Card VIIIb-1
55      1    7   13   19   25   31   37   43   49   55   61   62   63   64   65   66  Card VIIIc
56      7   11    8    0    0    2       0.0                                          Card VIIIa
57         0.0       0.0      20.0       0.0                                          Card VIIIb-1
58      6   12   18   24   30   36   42   48   54   60   66                           Card VIIIc
59               1         0         9         1                                          Card Xa
60       20244TEM AT NODE 14                                                            Card Xc
61       50244TEM AT NODE 32                                                            Card Xc
62       80244TEM AT NODE 50                                                            Card Xc
63      220244TEM AT NODE 16                                                            Card Xc
64      250244TEM AT NODE 34                                                            Card Xc
65      280244TEM AT NODE 52                                                            Card Xc
66      420244TEM AT NODE 18                                                            Card Xc
67      450244TEM AT NODE 36                                                            Card Xc
68      480244TEM AT NODE 54                                                            Card Xc
69         130         4                                                              Card Xd
```

4.3 Sample Problem 3: Sandia Cylinder Test

A basalt concrete cylinder, which is unconstrained on the outside of the cylinder, is analytically examined here. Figure 4.5a illustrates the initial configuration of the free (unconstrained) test specimen used by Acton, et al. (1981). The analytical model of the concrete specimen used in this study was subdivided into finite elements as shown in Figs. 4.5b and 4.5c. Because of symmetry only one-half of the specimen is modeled. Two meshes are given in order to illustrate the use of the rigid connection as an alternative to triangular elements when combining elements of two different sizes. The temperature dependent material properties of basalt concrete used in this example are summarized in Table 4.5. The input cards for the two simulations are given in Tables 4.6 and 4.7. One Gaussian integration point is used for the quadrilateral elements and also for the collapsed triangular elements in the stress calculations. The bottom at the centerline of the concrete model is assumed fixed and the remainder of centerline nodes are constrained to move along the z-axis. The input temperature is applied on the top surface of the cylinder. Because of the MgO insulation of the unconstrained model, zero heat flux is assumed on the boundaries of the concrete model.

Figure 4.6 shows the thermocouple readings up to 20 minutes for the free concrete cylinder given in Fig. 4.5a. Analytical temperatures (identical for both meshes) for the model are also plotted in Fig. 4.6. These temperatures were calculated from the assumed temperature being specified at the initial surface of the respective analytical model. The cracking history of the model is given in Fig. 4.7 for both meshes at 5 minute intervals up to 20 minutes. The influence of the mesh choice on the cracking pattern seems to be minimal.

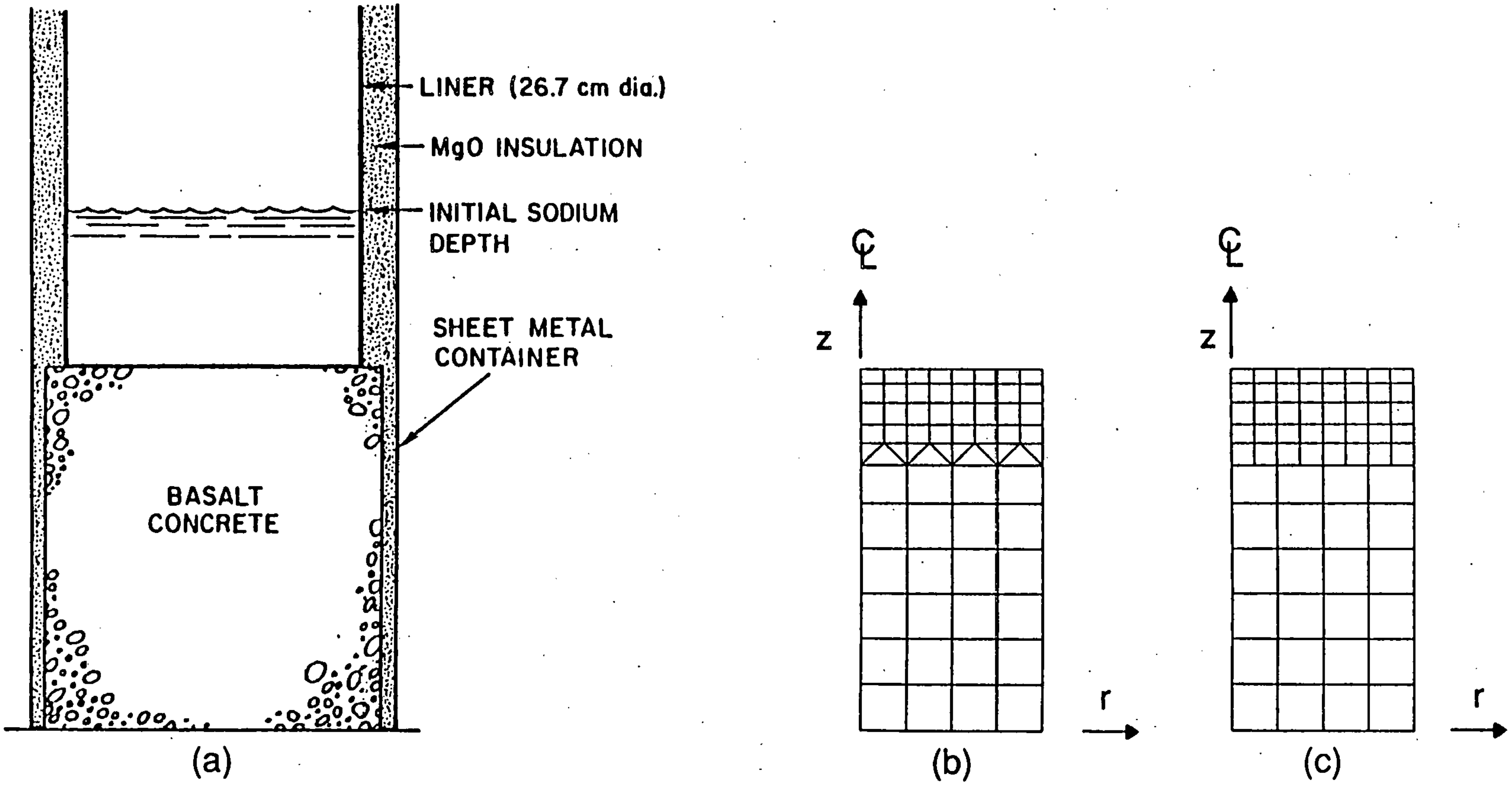


Figure 4.5 Cylinder Test Specimen Configuration and Analytical Models

Table 4.5 Basalt Concrete Properties for Cylinder (Sample Problems 3 and 4)

Temperature (°C)	Modulus of Elasticity (GPa)	Yield Stress (MPa)
21	21.5	27.58
93	15.0	20.69
371	7.3	15.51
538	2.2	8.27
700	0.557	4.13

Density $\rho = 2326$ kg/m^3

Poisson's ratio $\nu = 0.15$

Thermal expansion coefficient $\alpha = 9.2 \times 10^{-6}$ m/m/°C

Thermal conductivity $k = 1.85$ J/m/sec/°C

Specific heat $c = 949$ J/kg/°C

Table 4.6 Input Cards for Sample Problem 3 - 68 Element Model

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1  SANDIA CYLINDER TEST (NO CONSTRAINT) - 68 ELEMENT MODEL                           Card I
 2     80   68    1   12   60    2      20.0    1                                   Card II
 3      2    0             90                               5000  200  100    1       Card III
 4      1   13                                                                        Card IVa-13
 5       2.326      0.15    9.2E-6              0.0185     0.949       5.0       5.0  Card IVb-13
 6                   0.0       0.0       1.0       0.0      13.0       0.0       1.0  Card IVc-13
 7        21.0  25.00E10   0.00070    1.75E8   0.00125    2.45E8   0.00165    2.70E8  Card IVd-13
 8     0.00200    2.80E8   2.00000    2.80E8                                          Card IVd-13
 9        93.0  16.92E10   0.00065    1.10E8   0.00120    1.70E8   0.00175    2.00E8  Card IVd-13
10     0.00220    2.10E8   2.00000    2.10E8                                          Card IVd-13
11       371.0   8.42E10   0.00095    0.80E8   0.00160    1.20E8   0.00240    1.45E8  Card IVd-13
12     0.00310    1.55E8   2.00000    1.55E8                                          Card IVd-13
13       538.0   2.81E10   0.00160    0.45E8   0.00310    0.70E8   0.00450    0.80E8  Card IVd-13
14     0.00600    0.85E8   2.00000    0.85E8                                          Card IVd-13
15       700.0   0.92E10   0.00240    0.22E8   0.00460    0.35E8   0.00680    0.40E8  Card IVd-13
16     0.00900    0.42E8   2.00000    0.42E8                                          Card IVd-13
17      1              0.0       0.0                                                  Card V
18      5            15.24       0.0                                                  Card V
19      6              0.0      3.81                                                  Card V
20     10            15.24      3.81                                                  Card V
21     11              0.0      7.62                                                  Card V
22     15            15.24      7.62                                                  Card V
23     16              0.0     11.43                                                  Card V
24     20            15.24     11.43                                                  Card V
25     21              0.0     15.24                                                  Card V
26     25            15.24     15.24                                                  Card V
27     26              0.0     19.05                                                  Card V
28     30            15.24     19.05                                                  Card V
29     31              0.0     22.23                                                  Card V
30     35            15.24     22.23                                                  Card V
31     36              0.0     24.13                                                  Card V
32     44            15.24     24.13                                                  Card V
33     45              0.0     25.73                                                  Card V
34     53            15.24     25.73                                                  Card V
35     54              0.0     27.58                                                  Card V
```

Table 4.6 Input Cards for Sample Problem 3 - 68 Element Model (cont.)

```
               1         2         3         4         5         6         7         8
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
36       62          15.24     27.58                                                    Card V
37       63            0.0     29.21                                                    Card V
38       71          15.24     29.21                                                    Card V
39       72            0.0     30.48                                                    Card V
40       80          15.24     30.48                                                    Card V
41        1    1    2    7    6                        1   13    1                      Card VI
42        5    6    7   12   11                        1   13    1                      Card VI
43        9   11   12   17   16                        1   13    1                      Card VI
44       13   16   17   22   21                        1   13    1                      Card VI
45       17   21   22   27   26                        1   13    1                      Card VI
46       21   26   27   32   31                        1   13    1                      Card VI
47       25   31   37   36   36                        1   13    1                      Card VI
48       26   31   32   37   37                        1   13    1                      Card VI
49       27   32   38   37   37                        1   13    1                      Card VI
50       28   32   39   38   38                        1   13    1                      Card VI
51       29   32   33   39   39                        1   13    1                      Card VI
52       30   33   40   39   39                        1   13    1                      Card VI
53       31   33   41   40   40                        1   13    1                      Card VI
54       32   33   34   41   41                        1   13    1                      Card VI
55       33   34   42   41   41                        1   13    1                      Card VI
56       34   34   43   42   42                        1   13    1                      Card VI
57       35   34   35   43   43                        1   13    1                      Card VI
58       36   35   44   43   43                        1   13    1                      Card VI
59       37   36   37   46   45                        1   13    1                      Card VI
60       45   45   46   55   54                        1   13    1                      Card VI
61       53   54   55   64   63                        1   13    1                      Card VI
62       61   63   64   73   72                        1   13    1                      Card VI
63       68   70   71   80   79                        1   13    1                      Card VI
64         10110                                                                        Card VII
65         60100                                                                        Card VII
66        110100                                                                        Card VII
67        160100                                                                        Card VII
68        210100                                                                        Card VII
69        260100                                                                        Card VII
70        310100                                                                        Card VII
```

Table 4.6 Input Cards for Sample Problem 3 - 68 Element Model (cont.)

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
71      360100                                                                        Card VII
72      450100                                                                        Card VII
73      540100                                                                        Card VII
74      630100                                                                        Card VII
75      720100                                                                        Card VII
76      1    8    7    1    1    5                                                    Card VIIIa
77         0.0      21.0    1.2E+2     190.0    1.2E+3     360.0    2.4E+3     510.0  Card VIIIb-1
78      5.4E+3     550.0                                                              Card VIIIb-1
79     72                                                                             Card VIIIc
80             1         2        14         1                                        Card Xa
81      720204Z-DISP NODE 72                                                          Card Xb
82      800104R-DISP NODE 80                                                          Card Xb
83      610014EMR AT STA 1 ELE 61                                                     Card Xc
84      610024EMZ AT STA 1 ELE 61                                                     Card Xc
85      610044EMT AT STA 1 ELE 61                                                     Card Xc
86      530044EMT AT STA 1 ELE 53                                                     Card Xc
87      240044EMT AT STA 1 ELE 24                                                     Card Xc
88      610054STR AT STA 1 ELE 61                                                     Card Xc
89      610064STZ AT STA 1 ELE 61                                                     Card Xc
90      610084STT AT STA 1 ELE 61                                                     Card Xc
91      680084STT AT STA 1 ELE 68                                                     Card Xc
92      240084STT AT STA 1 ELE 24                                                     Card Xc
93      610154TEM AT STA 1 ELE 61                                                     Card Xc
94      680154TEM AT STA 1 ELE 68                                                     Card Xc
95      240154TEM AT STA 1 ELE 24                                                     Card Xc
96      710014INTERNAL ENERGY                                                         Card Xc
99          60         4                                                              Card Xd
```

Table 4.7 Input Cards for Sample Problem 3 - 64 Element Model

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1  SANDIA CYLINDER TEST (NO CONSTRAINT) - 64 ELEMENT MODEL                           Card I
 2     89   64    1   12   60    2      20.0    1    1                              Card II
 3      2    0             90                              5000  200  100    1      Card III
 4      1   13                                                                      Card IVa-13
 5       2.326      0.15    9.2E-6              0.0185     0.949       5.0       5.0  Card IVb-13
 6                   0.0       0.0       1.0       0.0      13.0       0.0       1.0  Card IVc-13
 7        21.0  25.00E10   0.00070    1.75E8   0.00125    2.45E8   0.00165    2.70E8  Card IVd-13
 8     0.00200    2.80E8   2.00000    2.80E8                                          Card IVd-13
 9        93.0  16.92E10   0.00065    1.10E8   0.00120    1.70E8   0.00175    2.00E8  Card IVd-13
10     0.00220    2.10E8   2.00000    2.10E8                                          Card IVd-13
11       371.0   8.42E10   0.00095    0.80E8   0.00160    1.20E8   0.00240    1.45E8  Card IVd-13
12     0.00310    1.55E8   2.00000    1.55E8                                          Card IVd-13
13       538.0   2.81E10   0.00160    0.45E8   0.00310    0.70E8   0.00450    0.80E8  Card IVd-13
14     0.00600    0.85E8   2.00000    0.85E8                                          Card IVd-13
15       700.0   0.92E10   0.00240    0.22E8   0.00460    0.35E8   0.00680    0.40E8  Card IVd-13
16     0.00900    0.42E8   2.00000    0.42E8                                          Card IVd-13
17      1              0.0       0.0                                                  Card V
18      5            15.24       0.0                                                  Card V
19      6              0.0      3.81                                                  Card V
20     10            15.24      3.81                                                  Card V
21     11              0.0      7.62                                                  Card V
22     15            15.24      7.62                                                  Card V
23     16              0.0     11.43                                                  Card V
24     20            15.24     11.43                                                  Card V
25     21              0.0     15.24                                                  Card V
26     25            15.24     15.24                                                  Card V
27     26              0.0     19.05                                                  Card V
28     30            15.24     19.05                                                  Card V
29     31              0.0     22.23                                                  Card V
30     35            15.24     22.23                                                  Card V
31     36              0.0     22.23                                                  Card V
32     44            15.24     22.23                                                  Card V
33     45              0.0     24.13                                                  Card V
34     53            15.24     24.13                                                  Card V
35     54              0.0     25.73                                                  Card V
```

Table 4.7 Input Cards for Sample Problem 3 - 64 Element Model (cont.)

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
36     62          15.24     25.73                                                    Card V
37     63            0.0     27.58                                                    Card V
38     71          15.24     27.58                                                    Card V
39     72            0.0     29.21                                                    Card V
40     80          15.24     29.21                                                    Card V
41     81            0.0     30.48                                                    Card V
42     89          15.24     30.48                                                    Card V
43      1    1    2    7    6                        1   13    1                      Card VI
44      5    6    7   12   11                        1   13    1                      Card VI
45      9   11   12   17   16                        1   13    1                      Card VI
46     13   16   17   22   21                        1   13    1                      Card VI
47     17   21   22   27   26                        1   13    1                      Card VI
48     21   26   27   32   31                        1   13    1                      Card VI
49     25   36   37   46   45                        1   13    1                      Card VI
50     33   45   46   55   54                        1   13    1                      Card VI
51     41   54   55   64   63                        1   13    1                      Card VI
52     49   63   64   73   72                        1   13    1                      Card VI
53     57   72   73   82   81                        1   13    1                      Card VI
54     64   79   80   89   88                        1   13    1                      Card VI
55       10110                                                                        Card VII
56       60100                                                                        Card VII
57      110100                                                                        Card VII
58      160100                                                                        Card VII
59      210100                                                                        Card VII
60      260100                                                                        Card VII
61      310100                                                                        Card VII
62      450100                                                                        Card VII
63      540100                                                                        Card VII
64      630100                                                                        Card VII
65      720100                                                                        Card VII
66      810100                                                                        Card VII
67      1    8    7    1    1    5                                                    Card VIIIa
68         0.0      21.0    1.2E+2     190.0    1.2E+3     360.0    2.4E+3     510.0  Card VIIIb-1
69      5.4E+3     550.0                                                              Card VIIIb-1
70     81                                                                             Card VIIIc
```

Table 4.7 Input Cards for Sample Problem 3 - 68 Element Model (cont.)

```
               1         2         3         4         5         6         7         8
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
71        1    5    9    1    1    1                                                    Card IXa
72       31                                                                             Card IXb
73       36                                                                             Card IXc
74             1         2        14         1                                          Card Xa
75        810204Z-DISP NODE 81                                                          Card Xb
76        890104R-DISP NODE 89                                                          Card Xb
77        570014EMR AT STA 1 ELE 57                                                     Card Xc
78        570024EMZ AT STA 1 ELE 57                                                     Card Xc
79        570044EMT AT STA 1 ELE 57                                                     Card Xc
80        490044EMT AT STA 1 ELE 49                                                     Card Xc
81        240044EMT AT STA 1 ELE 24                                                     Card Xc
82        570054STR AT STA 1 ELE 57                                                     Card Xc
83        570064STZ AT STA 1 ELE 57                                                     Card Xc
84        570084STT AT STA 1 ELE 57                                                     Card Xc
85        490084STT AT STA 1 ELE 49                                                     Card Xc
86        240084STT AT STA 1 ELE 24                                                     Card Xc
87        570154TEM AT STA 1 ELE 57                                                     Card Xc
88        640154TEM AT STA 1 ELE 64                                                     Card Xc
89        240154TEM AT STA 1 ELE 24                                                     Card Xc
90        670014INTERNAL ENERGY                                                         Card Xc
91            60         4                                                              Card Xd
```

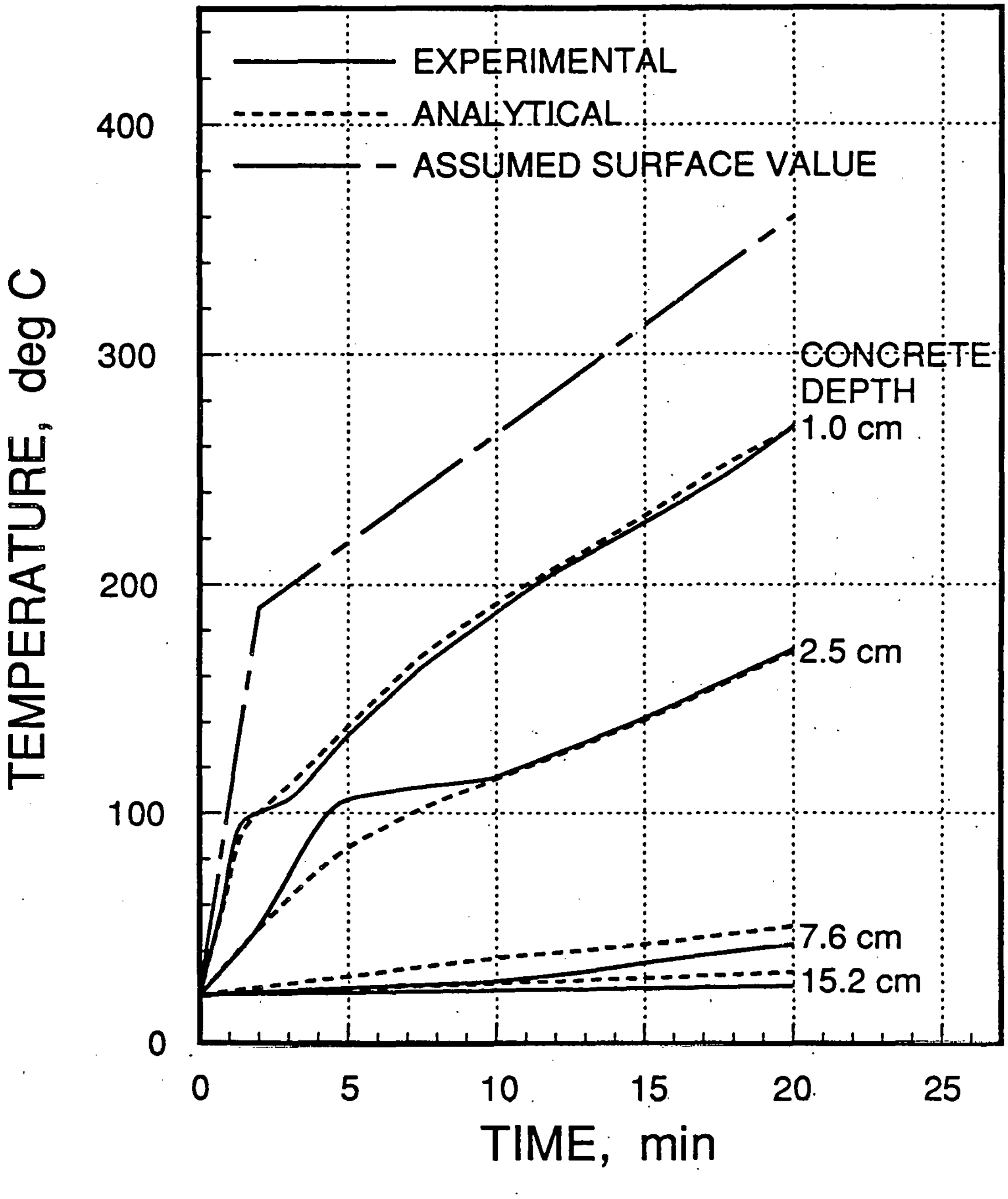


Figure 4.6 Analytical and Test Temperatures in Concrete Cylinder

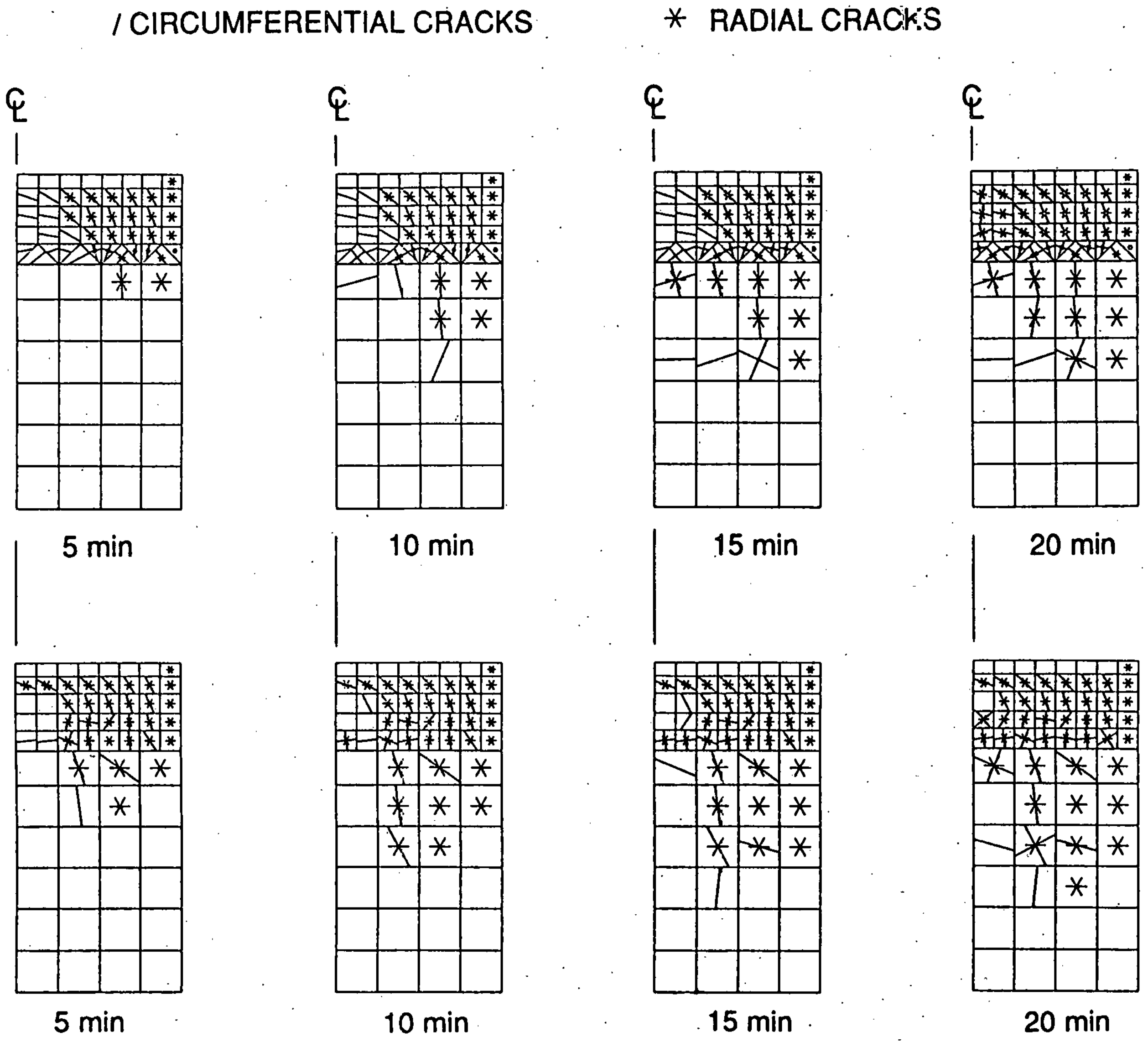


Figure 4.7 Cracking History of Concrete Cylinder Analytical Models

4.4 Sample Problem 4: Sandia Crucible Experiment

Dimensions of the test crucible employed by Acton, et al. (1979) are shown in Fig. 4.8. Liquid sodium of 600°C was dumped into the base cavity of the crucible resulting in a 13.2 cm deep pool. Measurements of temperature through the depth of the concrete slab were recorded and are reproduced in Fig. 4.9 which shows the temperature histories at different depths from the initial sodium-concrete interface. Posttest examination revealed an average surface erosion of approximately 5 cm deep in the crucible, as shown in Fig. 4.8. The cracking pattern of the crucible after the test is shown in Fig. 4.10.

The crucible model discretization used in the analysis is given in Fig. 4.11. The four-node quadrilateral continuum element with one point Gaussian integration is used. The temperature dependent material properties of basalt concrete used in this example are summarized in Table 4.5. Table 4.8 provides the input cards for this simulation.

The numerical solution yields temperature and stress results at each time step of the calculation. The temperature history of the crucible is compared with experimental results in Fig. 4.9. Cracking patterns are shown for times of 30 minutes, 60 minutes and 100 minutes in Fig. 4.11. Results of the cracking are in general, in good agreement with the observed cracks in Fig. 4.10.

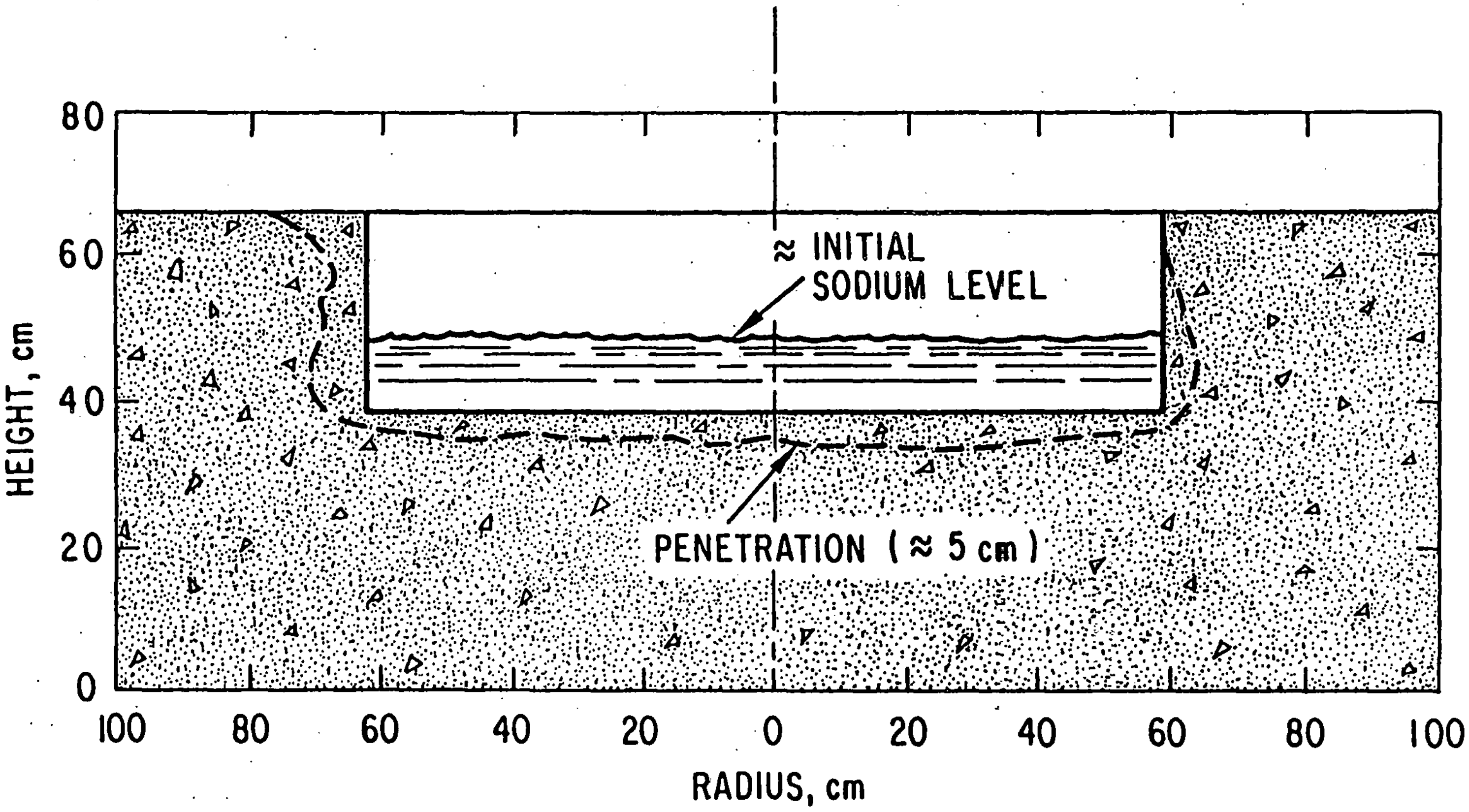


Figure 4.8 Test Crucible Configuration

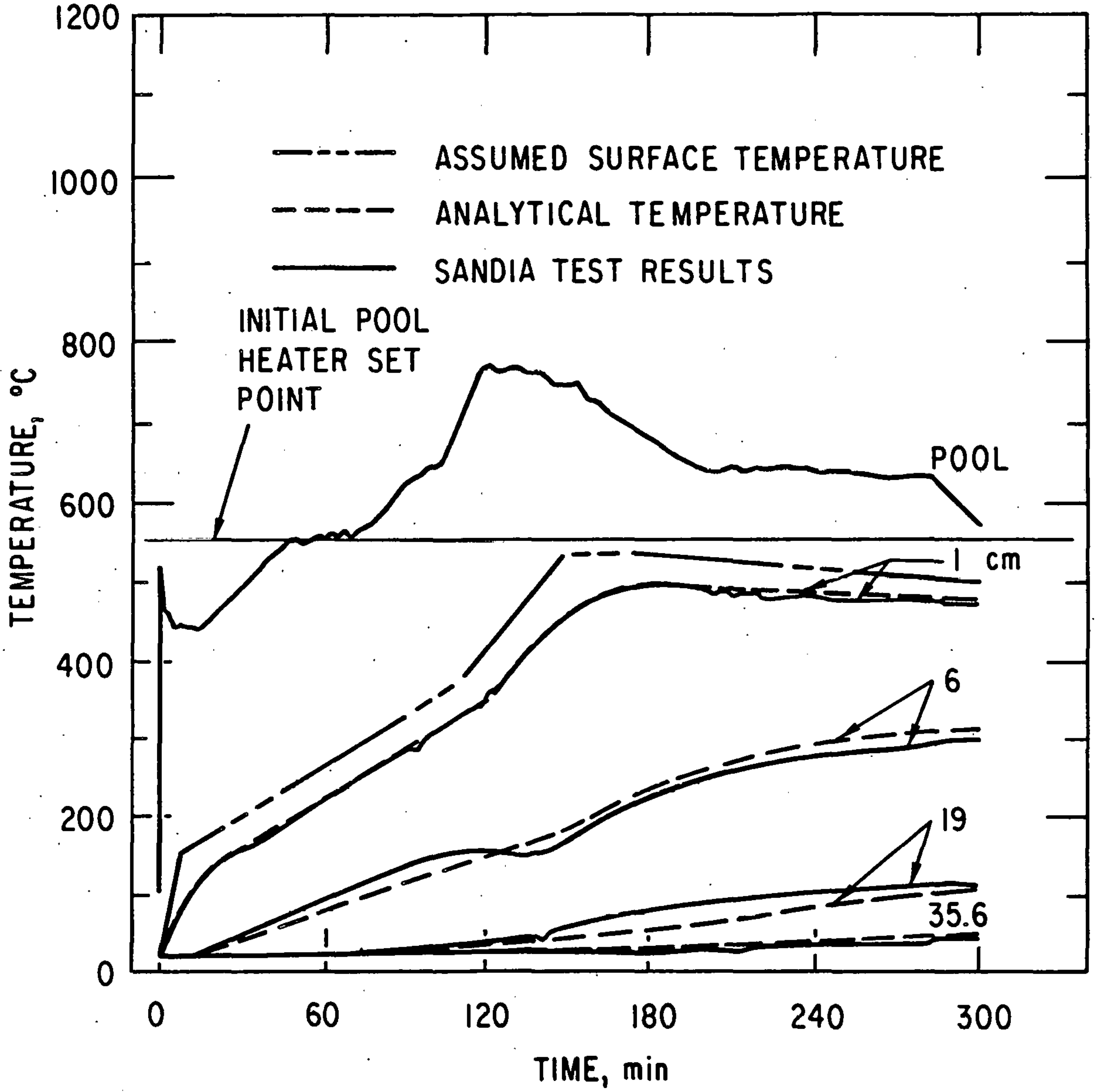
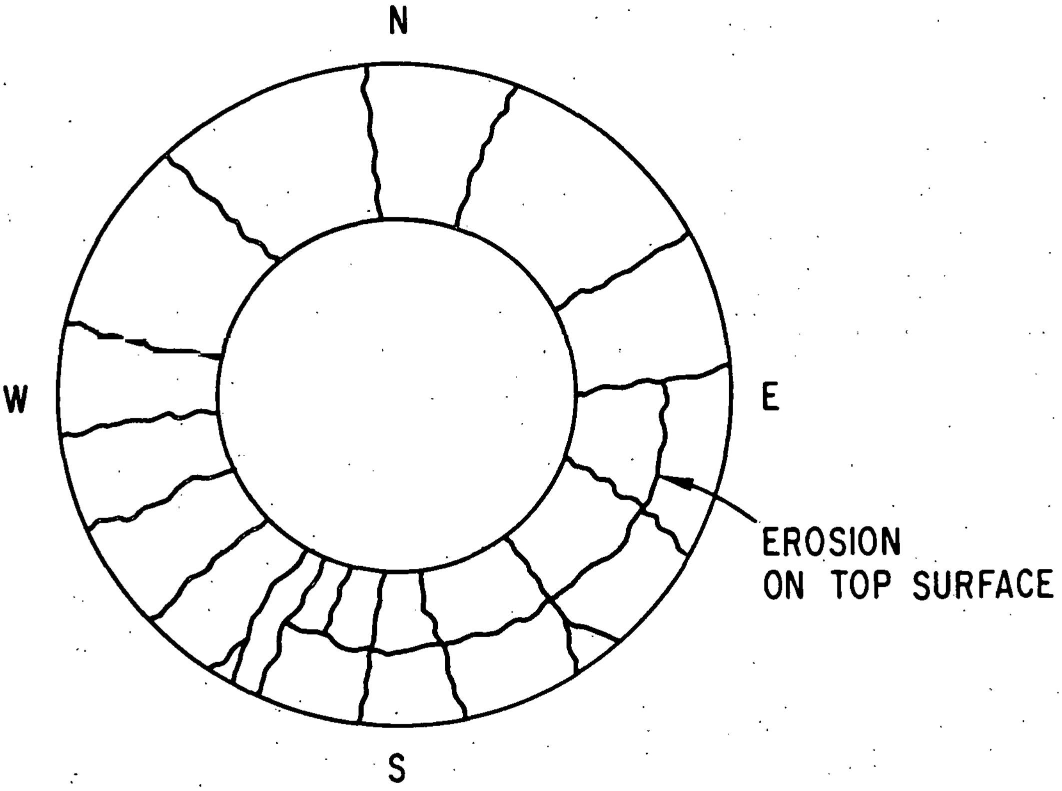
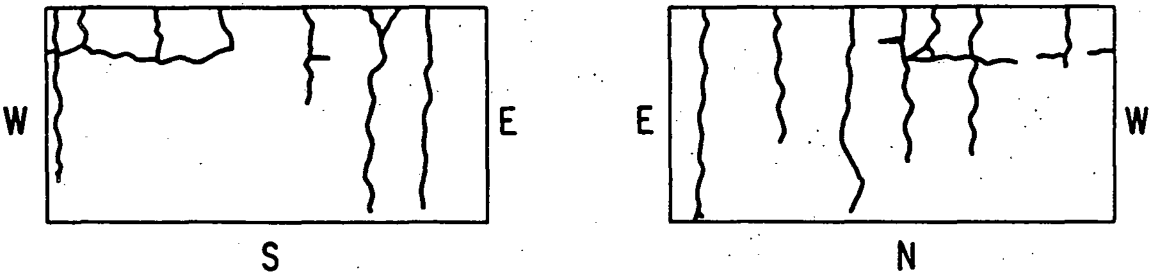


Figure 4.9 Experimental and Analytical Crucible Temperature Histories



A. TOP VIEW



B. SIDE VIEW

Figure 4.10 Crucible Test Cracking Pattern

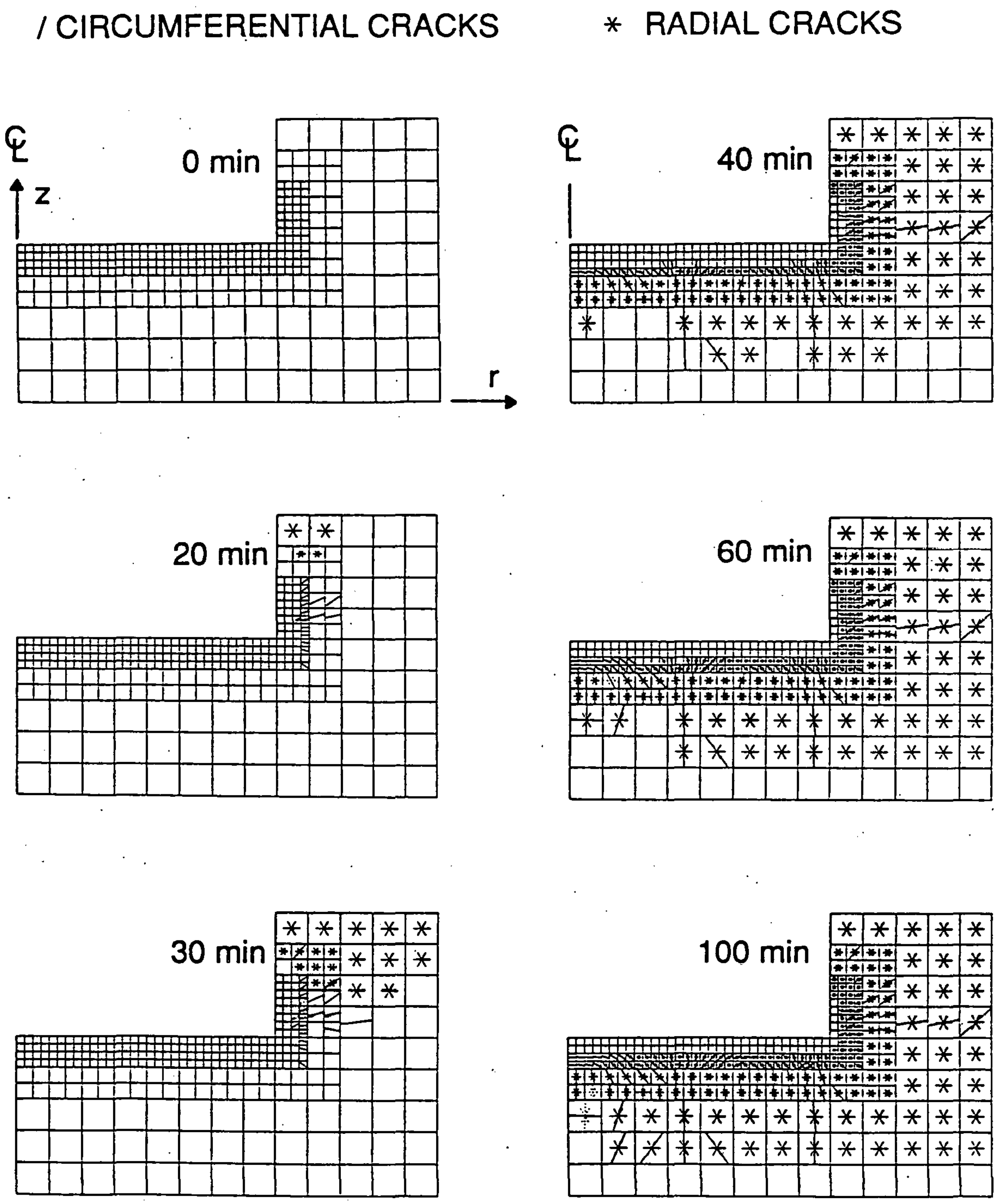


Figure 4.11 Analytical Model and Cracking Pattern of Crucible

Table 4.8 Input Cards for Sample Problem 4

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
SANDIA CRUCIBLE EXPERIMENT - WITH THERMAL CALCULATIONS                            Card I
  402  295    1   10  100    2        60.0    1    2                              Card II
    2    0             90                              2000  100  100    1        Card III
    1   13                                                                        Card IVa-13
     2.326      0.15    9.2E-6              0.0185     0.949       5.0       5.0  Card IVb-13
                 0.0       0.0       1.0       0.0      13.0       0.0       1.0  Card IVc-13
      21.0  25.00E10   0.00070    1.75E8   0.00125    2.45E8   0.00165    2.70E8  Card IVd-13
   0.00200    2.80E8   2.00000    2.80E8                                          Card IVd-13
      93.0  16.92E10   0.00065    1.10E8   0.00120    1.70E8   0.00175    2.00E8  Card IVd-13
   0.00220    2.10E8   2.00000    2.10E8                                          Card IVd-13
     371.0   8.42E10   0.00095    0.80E8   0.00160    1.20E8   0.00240    1.45E8  Card IVd-13
   0.00310    1.55E8   2.00000    1.55E8                                          Card IVd-13
     538.0   2.81E10   0.00160    0.45E8   0.00310    0.70E8   0.00450    0.80E8  Card IVd-13
   0.00600    0.85E8   2.00000    0.85E8                                          Card IVd-13
     700.0   0.92E10   0.00240    0.22E8   0.00460    0.35E8   0.00680    0.40E8  Card IVd-13
   0.00900    0.42E8   2.00000    0.42E8                                          Card IVd-13
    1            0.0       0.0                                                    Card V
    9           61.0       0.0                                                    Card V
   14           99.0       0.0                                                    Card V
   19           99.0      38.0                                                    Card V
   23           99.0      68.0                                                    Card V
   24            0.0       7.6                                                    Card V
   32           61.0       7.6                                                    Card V
   36           91.4       7.6                                                    Card V
   40           91.4      38.0                                                    Card V
   44           91.4      68.0                                                    Card V
   45            0.0      15.2                                                    Card V
   53           61.0      15.2                                                    Card V
   56           83.8      15.2                                                    Card V
   59           83.8      38.0                                                    Card V
   63           83.8      68.0                                                    Card V
   64            0.0      22.8                                                    Card V
   72           61.0      22.8                                                    Card V
   74           76.2      22.8                                                    Card V
   76           76.2      38.0                                                    Card V
```

Table 4.8 Input Cards for Sample Problem 4 (cont.)

```
               1         2         3         4         5         6         7         8
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
36       80           76.2      68.0                                                    Card V
37       81            0.0      22.8                                                    Card V
38       97           61.0      22.8                                                    Card V
39      101           76.2      22.8                                                    Card V
40      105           76.2      38.0                                                    Card V
41      111           76.2      60.5                                                    Card V
42      112            0.0      26.6                                                    Card V
43      128           61.0      26.6                                                    Card V
44      131           72.4      26.6                                                    Card V
45      134           72.4      38.0                                                    Card V
46      140           72.4      60.5                                                    Card V
47      141            0.0      30.4                                                    Card V
48      157           61.0      30.4                                                    Card V
49      159           68.6      30.4                                                    Card V
50      161           68.6      38.0                                                    Card V
51      167           68.6      60.5                                                    Card V
52      168           68.6      60.5                                                    Card V
53      169           68.6      68.0                                                    Card V
54      170            0.0      30.4                                                    Card V
55      202           61.0      30.4                                                    Card V
56      206           68.6      30.4                                                    Card V
57      210           68.6      38.0                                                    Card V
58      218           68.6      53.0                                                    Card V
59      219            0.0      32.3                                                    Card V
60      251           61.0      32.3                                                    Card V
61      254           66.7      32.3                                                    Card V
62      257           66.7      38.0                                                    Card V
63      265           66.7      53.0                                                    Card V
64      266            0.0      34.2                                                    Card V
65      298           61.0      34.2                                                    Card V
66      300           64.8      34.2                                                    Card V
67      302           64.8      38.0                                                    Card V
68      310           64.8      53.0                                                    Card V
69      311           64.8      53.0                                                    Card V
70      313           64.8      60.5                                                    Card V
```

Table 4.8 Input Cards for Sample Problem 4 (cont.)

```
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
 71    314            0.0      36.1                                                    Card V
 72    346           61.0      36.1                                                    Card V
 73    347           62.9      36.1                                                    Card V
 74    348           62.9      38.0                                                    Card V
 75    356           62.9      53.0                                                    Card V
 76    357            0.0      38.0                                                    Card V
 77    389           61.0      38.0                                                    Card V
 78    397           61.0      53.0                                                    Card V
 79    398           61.0      53.0                                                    Card V
 80    400           61.0      60.5                                                    Card V
 81    401           61.0      60.5                                                    Card V
 82    402           61.0      68.0                                                    Card V
 83      1    1    2   25   24                        1   13    1                      Card VI
 84     13   13   14   15   36                        1   13    1                      Card VI
 85     14   36   15   16   37                        1   13    1                      Card VI
 86     22   24   25   46   45                        1   13    1                      Card VI
 87     33   35   36   37   56                        1   13    1                      Card VI
 88     34   56   37   38   57                        1   13    1                      Card VI
 89     41   45   46   65   64                        1   13    1                      Card VI
 90     51   55   56   57   74                        1   13    1                      Card VI
 91     52   74   57   58   75                        1   13    1                      Card VI
 92     58   81   82  113  112                        1   13    1                      Card VI
 93     77  100  101  102  131                        1   13    1                      Card VI
 94     78  131  102  103  132                        1   13    1                      Card VI
 95     87  112  113  142  141                        1   13    1                      Card VI
 96    105  130  131  132  159                        1   13    1                      Card VI
 97    106  159  132  133  160                        1   13    1                      Card VI
 98    114  168   79   80  169                        1   13    1                      Card VI
 99    115  170  171  220  219                        1   13    1                      Card VI
100    150  205  206  207  254                        1   13    1                      Card VI
101    151  254  207  208  255                        1   13    1                      Card VI
102    162  219  220  267  266                        1   13    1                      Card VI
103    196  253  254  255  300                        1   13    1                      Card VI
104    197  300  255  256  301                        1   13    1                      Card VI
105    207  311  165  166  312                        1   13    1                      Card VI
```

Table 4.8 Input Cards for Sample Problem 4 (cont.)

```
               1         2         3         4         5         6         7         8
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
106     209  266  267  315  314                        1   13    1                      Card VI
107     242  299  300  301  347                        1   13    1                      Card VI
108     243  347  301  302  348                        1   13    1                      Card VI
109     252  314  315  358  357                        1   13    1                      Card VI
110     284  346  347  348  389                        1   13    1                      Card VI
111     285  389  348  349  390                        1   13    1                      Card VI
112     293  398  311  312  399                        1   13    1                      Card VI
113     295  401  168  169  402                        1   13    1                      Card VI
114        10100                                                                        Card VII
115       240100                                                                        Card VII
116       450100                                                                        Card VII
117       640100                                                                        Card VII
118      1120100                                                                        Card VII
119      1410100                                                                        Card VII
120      2190100                                                                        Card VII
121      2660100                                                                        Card VII
122      3140100                                                                        Card VII
123      3570100                                                                        Card VII
124       1   39    7    1    1    6                                                    Card VIIIa
125         0.0      21.0   0.06E+4     160.0   0.66E+4     370.0   0.90E+4     530.0  Card VIIIb-1
126     1.08E+4     530.0 1.8001E+4     500.0                                          Card VIIIb-1
127     357                                                                             Card VIIIc
128       1   18   35    0    0    1                                                    Card IXa
129      64   65   66   67   68   69   70   71   72   73   74   75   76   77   78   79  Card IXb
130     168  401                                                                        Card IXb
131      81   82   83   84   85   86   87   88   89   90   91   92   93   94   95   96  Card IXc
132      97   98   99  100  101  102  103  104  105  106  107  108  109  110  111  140  Card IXc
133     167  313  400                                                                   Card IXc
134       2   27   53    0    0    1                                                    Card IXa
135     141  142  143  144  145  146  147  148  149  150  151  152  153  154  155  156  Card IXb
136     157  158  159  160  161  162  163  164  165  311  398                           Card IXb
137     170  171  172  173  174  175  176  177  178  179  180  181  182  183  184  185  Card IXc
138     186  187  188  189  190  191  192  193  194  195  196  197  198  199  200  201  Card IXc
139     202  203  204  205  206  207  208  209  210  211  212  213  214  215  216  217  Card IXc
140     218  265  310  356  397                                                         Card IXc
```

Table 4.8 Input Cards for Sample Problem 4 (cont.)

```
               1         2         3         4         5         6         7         8
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
141            1         3         8         1                                          Card Xa
142      3570204Z-DISP NODE 357                                                         Card Xb
143       230104R-DISP NODE 23                                                          Card Xb
144       230204Z-DISP NODE 23                                                          Card Xb
145      2520064STZ AT STA 1 ELE 252                                                    Card Xc
146      2090064STZ AT STA 1 ELE 209                                                    Card Xc
147      1620064STZ AT STA 1 ELE 162                                                    Card Xc
148       870064STZ AT STA 1 ELE 87                                                     Card Xc
149      2520154TEM AT STA 1 ELE 252                                                    Card Xc
150      1620154TEM AT STA 1 ELE 162                                                    Card Xc
151       410154TEM AT STA 1 ELE 41                                                     Card Xc
152      2970014APPLIED TEMPERATURE                                                     Card Xc
153          100         4                                                              Card Xd
```

4.5 Sample Problem 5: Reinforced Concrete Beam

The reinforced beam element and reinforced continuum element are investigated in comparison with test results given by Bresler and Scordelis (1964) of a reinforced concrete slender beam. The test data pertains to a simply supported concrete beam reinforced by four steel bars of 1.0 in^2 area each, as shown in Fig. 4.12. The beam is subjected to a gradually increasing mid-span load.

The analytical models take advantage of the symmetry of the test specimen and model one-half of the beam. It represents the beam from the center to the support. The material properties are given in Table 4.9. In the first model four reinforced elements (2 layers of reinforcement) of equal size are utilized. The input cards for this mesh are given in Table 4.10. The second model consists of 40 continuum elements with smeared reinforcement in the bottom two layers. The input cards for this mesh are given in Table 4.11.

A comparison of test load-deflection and the analytical predictions is shown in Fig. 4.13. The deviations of the analytical results from the test data, as loading increases, are attributed to shear cracking and debonding limitations in the analytical models. The agreement of test data and analytical results is quite good over the range for which the formulation was intended.

Table 4.9 Material Properties for Concrete Beam (Sample Problem 5)

Concrete Young's modulus	$E = 3.1 \times 10^6$ psi
Concrete Poisson's ratio	$\nu = 0.2$
Concrete compression strength	$f'_c = 3500$ psi
Concrete tensile strength	$f'_t = 333$ psi
Concrete tensile failure strain	$\varepsilon_{ut} = 0.0007$ in/in
Rebar Young's modulus	$E = 27.8 \times 10^6$ psi
Rebar yield stress	$\sigma_Y = 6.0 \times 10^4$ psi
Rebar ultimate stress	$\sigma_u = 1.44 \times 10^5$ psi

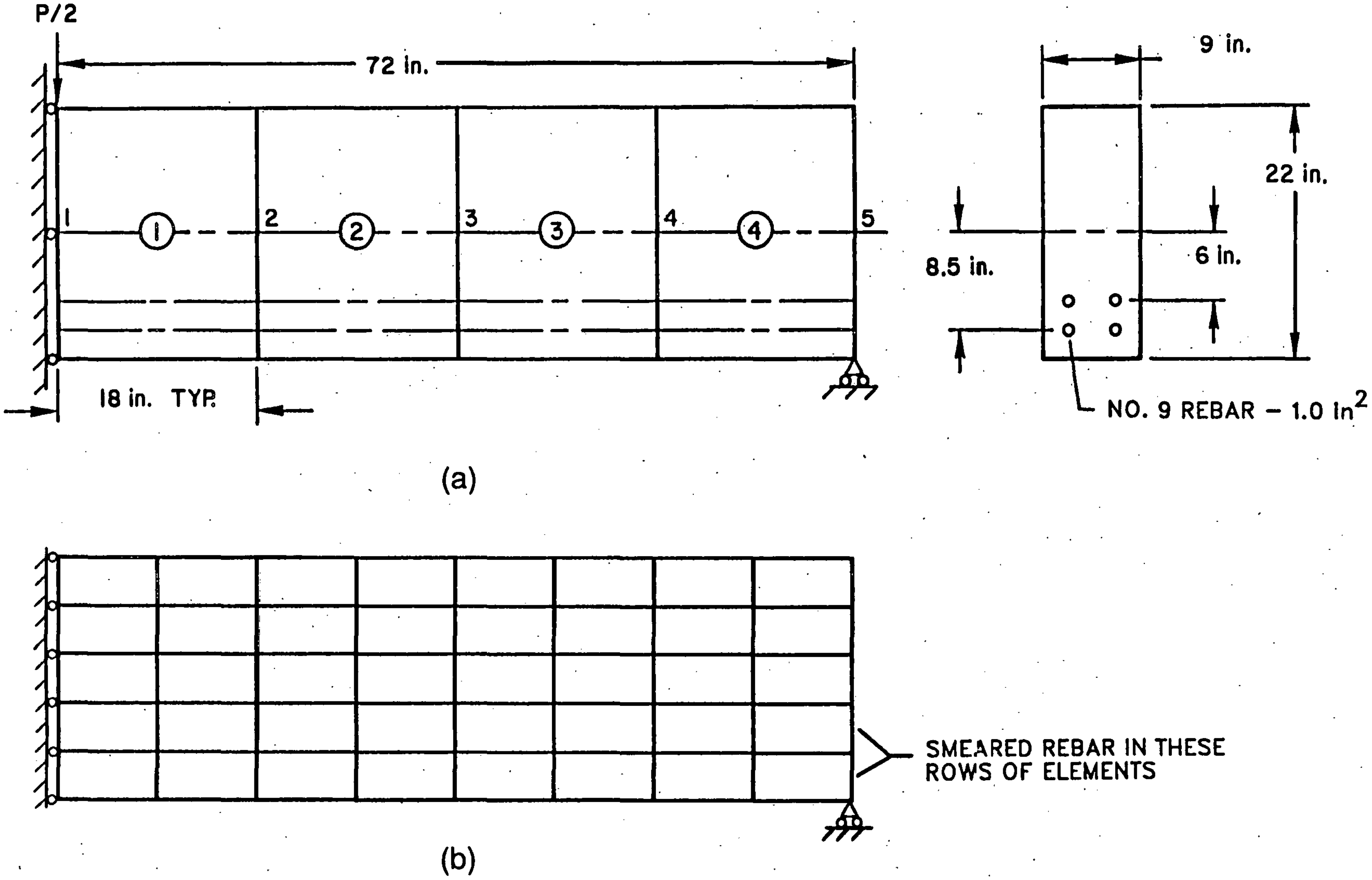


Figure 4.12 Simply Supported Reinforced Concrete Beam Models

Table 4.10 Input Cards for Sample Problem 5 - Beam Element Model

```
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1   REINFORCED CONCRETE BEAM - BEAM ELEMENT MODEL                                     Card I
 2      10    4    1    3   25    2       1.0    1                                     Card II
 3       2    0             90                               1000  100  100    1       Card III
 4       1    4                                                                        Card IVa-4
 5     2.25E-4       0.2                                               1.0       4.0  Card IVb-4
 6         9.0      22.0       0.0       1.0       0.0      11.0       3.0       5.0  Card IVc-4
 7        70.0    3.25E6  0.000667     2.2E3   0.00152     3.4E3     0.002     3.5E3  Card IVd-4
 8         1.0     3.5E3                                                              Card IVd-4
 9         1.0   0.11428      1.15       0.8       4.2   -0.0007    -0.006            Card IVe-4
10      7.4E-4                 1.0       4.0                                          Card IVg-4
11        70.0   2.778E7   0.00216     6.0E4    0.0056     9.6E4      0.02    13.3E4  Card IVh-4
12        0.06    14.4E4                                                              Card IVh-4
13         2.0                                                                        Card IVi-4
14         2.0      -8.5       0.0                                                    Card IVj-4
15         2.0      -6.0       0.0                                                    Card IVj-4
16       1               0.0       0.0                                                Card V
17       5              72.0       0.0                                                Card V
18       6               0.0       0.0                                                Card V
19      10               0.0       0.0                                                Card V
20       1    1    2    7    6                        1    4    1                      Card VI
21       4    4    5   10    9                        1    4    1                      Card VI
22       10100                                                                        Card VII
23       50010                                                                        Card VII
24       60110                                                                        Card VII
25       1    1    4    0    0    1                                                    Card VIIIa
26    30.0  -40000.0                                                                  Card VIIIb-1
27       1                                                                             Card VIIIc
28           1         3         1         1                                          Card Xa
29        10204Y-DISP NODE 1                                                           Card Xb
30        10234Y-FORCE NODE 1                                                          Card Xb
31        50244Y-FORCE NODE 5                                                          Card Xb
32        90024INTERNAL ENERGY                                                         Card Xc
33          25         4                                                              Card Xd
```

Table 4.11 Input Cards for Sample Problem 5 - Continuum Element Model

```
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1   REINFORCED CONCRETE BEAM - CONTINUUM ELEMENT MODEL                                Card I
 2      54   40    2    7   25    2       1.0    1                                     Card II
 3       2    0             90                               2000  500  100    1       Card III
 4       1    3                                                                        Card IVa-3
 5      2.25E-4       0.2                                               1.0       4.0  Card IVb-3
 6          9.0       0.0       0.0       1.0       0.0      11.0       3.0       1.0  Card IVc-3
 7         70.0    3.25E6  0.000667     2.2E3   0.00152     3.4E3     0.002     3.5E3  Card IVd-3
 8          1.0     3.5E3                                                              Card IVd-3
 9          1.0   0.11428      1.15       0.8       4.2   -0.0007    -0.006            Card IVe-3
10       7.4E-4                 1.0       4.0                                          Card IVg-3
11         70.0   2.778E7   0.00216     6.0E4    0.0056     9.6E4      0.02    13.3E4  Card IVh-3
12         0.06    14.4E4                                                              Card IVh-3
13       2    3                                                                        Card IVa-3
14      2.25E-4       0.2                                               1.0       4.0  Card IVb-3
15          9.0       0.0       0.0       1.0       0.0      11.0       1.0       1.0  Card IVc-3
16         70.0    3.25E6  0.000667     2.2E3   0.00152     3.4E3     0.002     3.5E3  Card IVd-3
17          1.0     3.5E3                                                              Card IVd-3
18          1.0   0.11428      1.15       0.8       4.2   -0.0007    -0.006            Card IVe-3
19       1               0.0       0.0                                                 Card V
20       9              72.0       0.0                                                 Card V
21      10               0.0       4.4                                                 Card V
22      18              72.0       4.4                                                 Card V
23      19               0.0       8.8                                                 Card V
24      27              72.0       8.8                                                 Card V
25      28               0.0      13.2                                                 Card V
26      36              72.0      13.2                                                 Card V
27      37               0.0      17.6                                                 Card V
28      45              72.0      17.6                                                 Card V
29      46               0.0      22.0                                                 Card V
30      54              72.0      22.0                                                 Card V
31       1    1    2   11   10  505                   1    3    1                      Card VI
32       9   10   11   20   19  505                   1    3    1                      Card VI
33      17   19   20   29   28                        2    3    1                      Card VI
34      25   28   29   38   37                        2    3    1                      Card VI
35      33   37   38   47   46                        2    3    1                      Card VI
```

Table 4.11 Input Cards for Sample Problem 5 - Continuum Element Model (cont.)

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
36     40   44   45   54   53                        2    3    1                      Card VI
37       10100                                                                        Card VII
38      100100                                                                        Card VII
39      190100                                                                        Card VII
40      280100                                                                        Card VII
41      370100                                                                        Card VII
42      460100                                                                        Card VII
43       90010                                                                        Card VII
44      1    1    4    0    0    1                                                    Card VIIIa
45   30.0       -40000.0                                                              Card VIIIb-1
46     46                                                                             Card VIIIc
47           1         3         1         1                                          Card Xa
48      460204Y-DISP NODE 46                                                          Card Xb
49      460234Y-FORCE NODE 46                                                         Card Xb
50       90244Y-FORCE NODE 9                                                          Card Xb
51      450024INTERNAL ENERGY                                                         Card Xc
52          25         4                                                              Card Xd
```

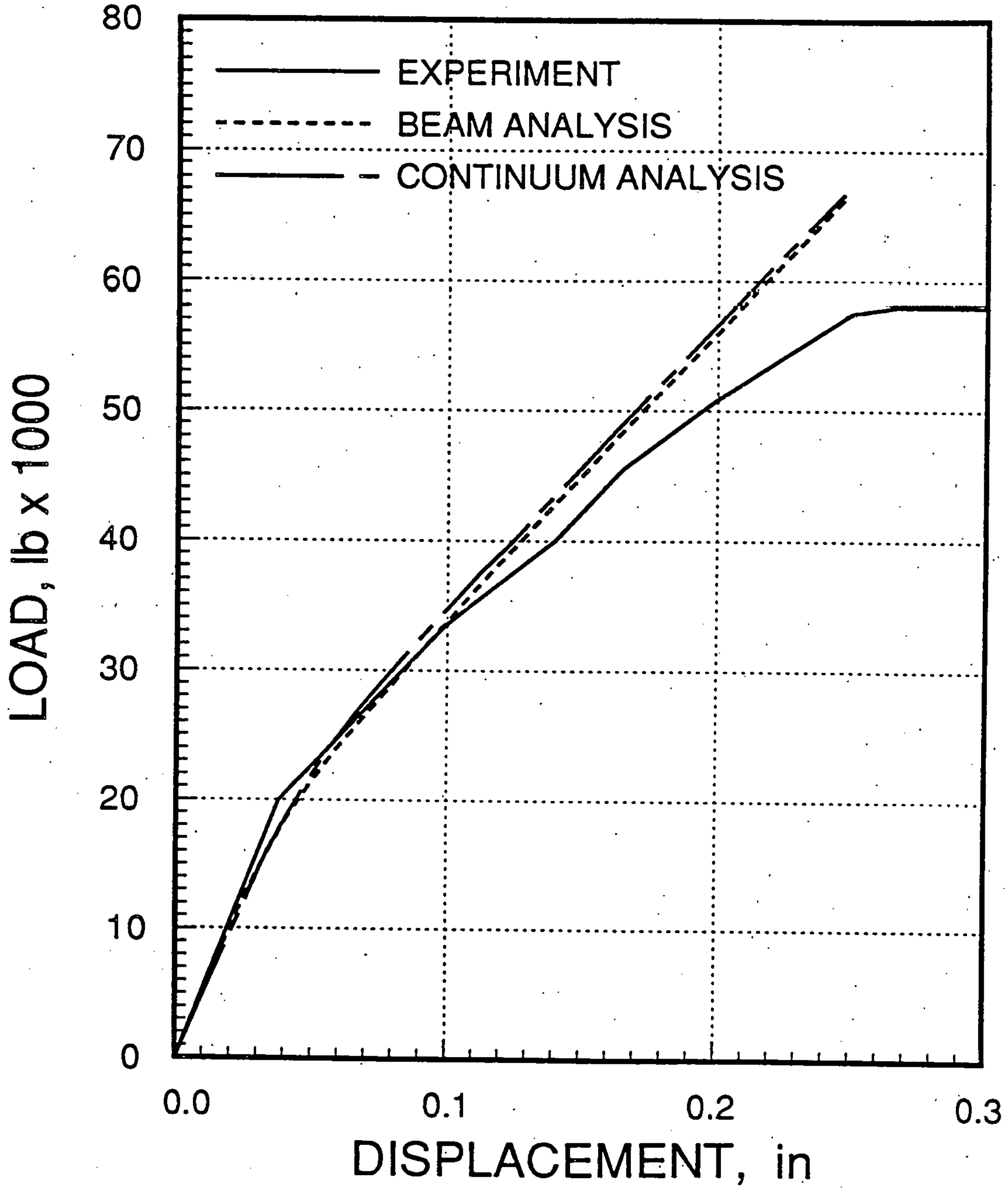


Figure 4.13 Load Versus Deflection for Concrete Beam

4.6 Sample Problem 6: Reinforced Concrete Containment

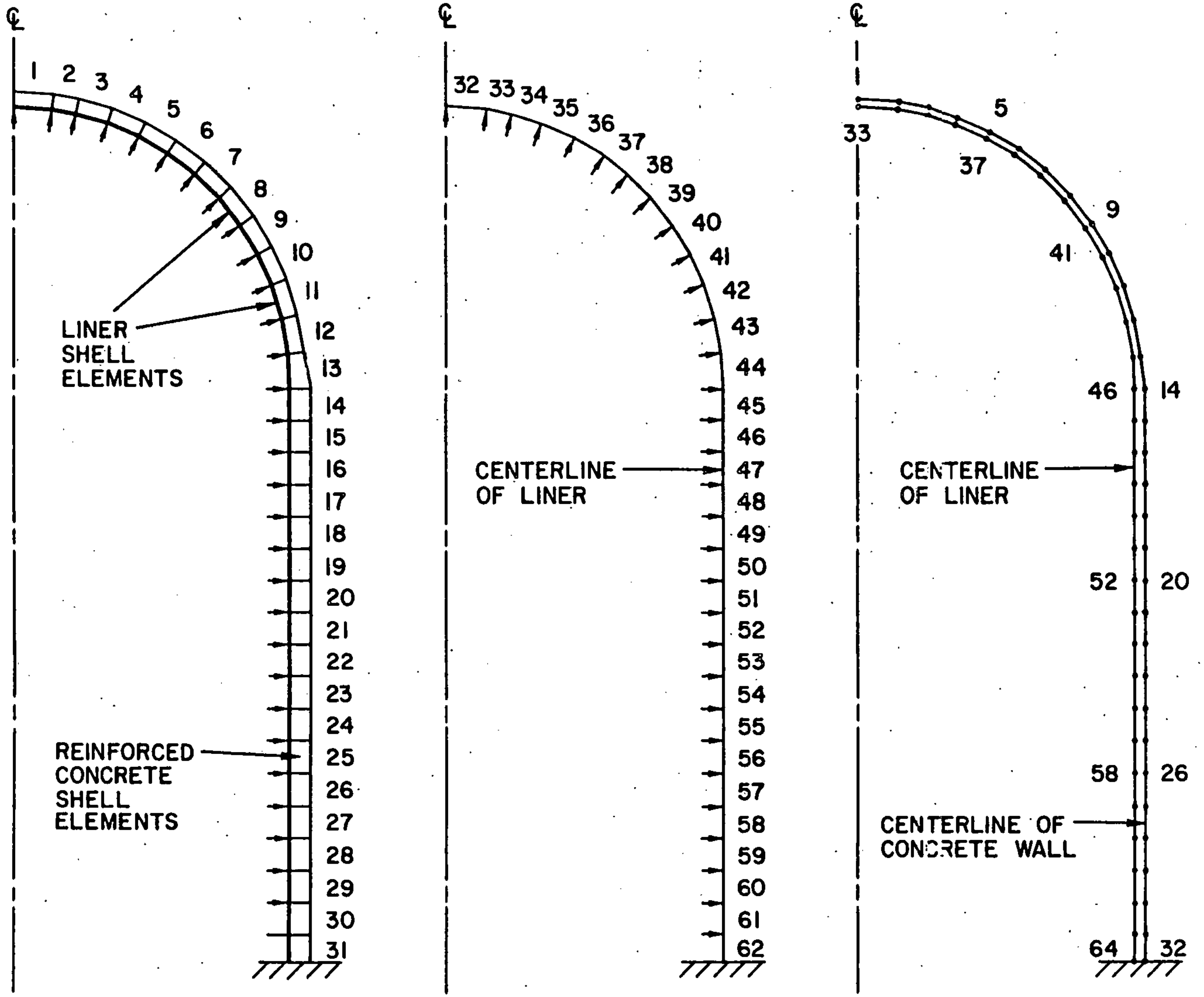
A scaled reinforced concrete containment model is shown in Fig. 4.14. The analysis of this model is considered for the following three different loading conditions: (1) static internal pressurization to failure with the complete structure at 70°F, (2) static internal pressurization to failure with the structure at 400°F internally and 70°F externally (linear variation thru the thickness) with a steady state thermal field, (3) dynamic threshold failure pressure subjected internally.

The finite element model shown in Fig. 4.14 consists only of the axisymmetric cylindrical vessel and a spherical dome. The size of the containment is given in Table 4.12. This model consists of 31 reinforced concrete shell elements: 13 of them representing the 8 inch thick spherical dome, and 18 elements representing the 8 inch thick cylinder. A liner on the inside surface of the vessel is made up of steel elements. The liner elements, which are offset from the concrete elements through a rigid connection, have a thickness of 0.10 inches in the dome and in the cylinder. The number of reinforcement layers in each concrete shell element is four. Two hoop rebar of 1.0 in^2 and two meridional rebar of 12.0 in^2 in area are used. The material properties for the concrete, rebar and liner are given in Tables 4.13 to 4.15, respectively for the temperature range discussed above. The input cards for the three loadings are given in Tables 4.16 to 4.18.

Table 4.12 Dimensions of Containment (Sample Problem 6)

Cylinder	
Concrete shell radius	r_c = 136 in
Steel shell radius	r_s = 132 in
Concrete shell height	h_c = 297 in
Dome	
Concrete shell radius	r_c = 136 in
Steel shell radius	r_s = 132 in

Note: All radii measured to the shell centerline.



ELEMENT NUMBERS NODE NUMBERS

Figure 4.14 Scaled Reinforced Concrete Containment Model

Table 4.13 Concrete Material Properties at Various Temperatures (Sample Problem 6)

	Temperature (°F)		
Material Property	70	250	700
Young's modulus (ksi)	4800	2300	1200
Poisson's ratio	0.2	0.2	0.2
Tensile strength (psi)	500	353	250
Coefficient of thermal expansion (in/in/°F)	$5.5\text{x}10^{-6}$	$5.5\text{x}10^{-6}$	$5.5\text{x}10^{-6}$
Unconfined compressive stress-strain curve (engineering valves)	70	250	700
Yield stress (psi)	3400	2400	1700
Ultimate stress (psi)	6800	4800	3400
Strain at ultimate stress (in/in)	$2.3\text{x}10^{-3}$	$2.97\text{x}10^{-3}$	$3.72\text{x}10^{-3}$
Ultimate strain at zero strength (in/in)	0.006	0.006	0.006

Table 4.14 Rebar Material Properties at Various Temperatures (Sample Problem 6)

	Temperature (°F)		
Material Property	70	400	800
Young's modulus (ksi)	31000	28500	25700
Coefficient of thermal expansion (in/in/°F)	6.2×10^{-6}	6.2×10^{-6}	6.2×10^{-6}
Bilinear engineering stress-strain curve	70	400	800
Yield stress (psi)	66.6	56.6	51.3
Ultimate stress (psi)	82.3	73.1	61.2
Ultimate strain (in/in)	0.02	0.02	0.02

Table 4.15 Liner Material Properties at Various Temperatures (Sample Problem 6)

	Temperature (°F)		
Material Property	70	400	800
Young's modulus (ksi)	30000	27900	25200
Poisson's ratio	0.3	0.3	0.3
Coefficient of thermal expansion (in/in/°F)	6.5×10^{-6}	6.5×10^{-6}	6.5×10^{-6}
Bilinear engineering stress-strain curve	70	400	800
Yield stress (psi)	50.2	45.2	40.2
Ultimate stress (psi)	56.0	51.0	44.9
Ultimate strain (in/in)	0.03	0.03	0.03

Table 4.16 Input Cards for Sample Problem 6 - Static Loading

```
               1         2         3         4         5         6         7         8
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1    REINFORCED CONCRETE SHELL VESSEL - STATIC LOADING                                 Card I
 2      128   62    2    4   10    2       1.0    1    1                                Card II
 3        2    0            90                              10000  200   10    1       Card III
 4        1   14                                                                        Card IVa-14
 5       2.25E-4       0.2                                             1.0       3.0  Card IVb-14
 6                     8.0       0.0       1.0                13.0       3.0       5.0  Card IVc-14
 7          70.0     4.8E6 7.0833E-4     3.4E3    0.0023     6.8E3       1.0     6.8E3  Card IVd-14
 8           1.0   0.07353      1.15       0.8       4.2   -0.0007    -0.006            Card IVe-14
 9        7.5E-4                 1.0       2.0                                          Card IVg-14
10          70.0     3.1E7  0.002148    6.66E4      0.02    8.23E4                      Card IVh-14
11           4.0                                                                        Card IVi-14
12          12.0      -2.5                                                              Card IVj-14
13           1.0      -3.0      90.0                                                    Card IVj-14
14          12.0       2.5                                                              Card IVj-14
15           1.0       3.0      90.0                                                    Card IVj-14
16        2   11                                                                        Card IVa-11
17        7.5E-4                 0.3                                   1.0       2.0  Card IVb-11
18                     0.1       0.0       0.0                 3.0       2.0       5.0  Card IVc-11
19          70.0     3.0E7  0.001673    5.02E4      0.03     5.6E4                      Card IVd-11
20        1    1     136.0      90.0       0.0     297.0                                Card V
21       14    1     136.0       0.0       0.0     297.0                                Card V
22       15          136.0     280.5                                                    Card V
23       32          136.0       0.0                                                    Card V
24       33    1     132.0      90.0       0.0     297.0                                Card V
25       46    1     132.0       0.0       0.0     297.0                                Card V
26       47          132.0     280.5                                                    Card V
27       64          132.0       0.0                                                    Card V
28       65            0.0       0.0                                                    Card V
29      128            0.0       0.0                                                    Card V
30        1    1    2   66   65                        1   14    1                      Card VI
31       32   33   34   98   97                        2   11    1                      Card VI
32       62   63   64  128  127                        2   11    1                      Card VI
33         10100                                                                        Card VII
34        320110                                                                        Card VII
35        650110                                                                        Card VII
```

Table 4.16 Input Cards for Sample Problem 6 - Static Loading (cont.)

```
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
36       960110                                                                          Card VII
37       1   32    1    3    1    2                                                      Card VIIIa
38          0.0       0.0     100.0    -500.0                                            Card VIIIb-1
39      33                                                                               Card VIIIc
40       1   32   32    1    1    3                                                      Card IXa
41       1                                                                               Card IXb
42      33                                                                               Card IXc
43            1         5         0         1                                            Card Xa
44        10204Z-DISP NODE 1                                                             Card Xb
45       140104R-DISP NODE 14                                                            Card Xb
46       140204Z-DISP NODE 14                                                            Card Xb
47       230104R-DISP NODE 23                                                            Card Xb
48       230204Z-DISP NODE 23                                                            Card Xb
49           10         4                                                                Card Xd
```

Table 4.17 Input Cards for Sample Problem 6 - Thermomechanical Loading

```
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1   REINFORCED CONCRETE SHELL VESSEL - THERMOMECHANICAL LOADING                       Card I
 2     128   62    2    4   34    2         1.0    6    1                              Card II
 3       2    0             90                              10000  200   10    1       Card III
 4       1   14                                                                        Card IVa-14
 5     2.25E-4       0.2    5.5E-6                                     3.0       3.0  Card IVb-14
 6                   8.0       0.0       1.0                13.0       3.0       5.0  Card IVc-14
 7        70.0     4.8E6 7.0833E-4     3.4E3    0.0023     6.8E3       1.0     6.8E3  Card IVd-14
 8       250.0     2.3E6 1.0435E-3     2.4E3 0.0029703     4.8E3       1.0     4.8E3  Card IVd-14
 9       700.0     1.2E6 1.4167E-3     1.7E3 0.0037167     3.4E3       1.0     3.4E3  Card IVd-14
10         1.0   0.07353      1.15       0.8       4.2   -0.0007    -0.006            Card IVe-14
11      7.5E-4    6.2E-6       3.0       2.0                                          Card IVg-14
12        70.0    3.10E7  0.002148    6.66E4      0.02    8.23E4                      Card IVh-14
13       400.0    2.85E7  0.001986    5.66E4      0.02    7.31E4                      Card IVh-14
14       800.0    2.57E7  0.001996    5.13E4      0.02    6.12E4                      Card IVh-14
15         4.0                                                                        Card IVi-14
16        12.0      -2.5                                                              Card IVj-14
17         1.0      -3.0      90.0                                                    Card IVj-14
18        12.0       2.5                                                              Card IVj-14
19         1.0       3.0      90.0                                                    Card IVj-14
20       2   11                                                                        Card IVa-11
21      7.5E-4                 0.3    6.5E-6                           3.0       2.0  Card IVb-11
22                   0.1       0.0       0.0                 3.0       2.0       5.0  Card IVc-11
23        70.0    3.00E7  0.001673    5.02E4      0.03    5.60E4                      Card IVd-11
24       400.0    2.79E7  0.001620    4.52E4      0.03    5.10E4                      Card IVd-11
25       800.0    2.52E7  0.001595    4.02E4      0.03    4.49E4                      Card IVd-11
26       1    1     136.0      90.0       0.0     297.0                                Card V
27      14    1     136.0       0.0       0.0     297.0                                Card V
28      15          136.0     280.5                                                    Card V
29      32          136.0       0.0                                                    Card V
30      33    1     132.0      90.0       0.0     297.0                                Card V
31      46    1     132.0       0.0       0.0     297.0                                Card V
32      47          132.0     280.5                                                    Card V
33      64          132.0       0.0                                                    Card V
34      65            0.0       0.0                                                    Card V
35     128            0.0       0.0                                                    Card V
```

Table 4.17 Input Cards for Sample Problem 6 - Thermomechanical Loacing (cont.)

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
36      1    1    2   66   65                        1   14    1                      Card VI
37     32   33   34   98   97                        2   11    1                      Card VI
38     62   63   64  128  127                        2   11    1                      Card VI
39       10100                                                                        Card VII
40      320110                                                                        Card VII
41      650110                                                                        Card VII
42      960110                                                                        Card VII
43      1   32    1    3    1    2                                                    Card VIIIa
44        10.0       0.0     110.0    -500.0                                          Card VIIIb-1
45     33                                                                             Card VIIIc
46      2   32    7    3    5    4                                                    Card VIIIa
47         0.0      70.0      10.0     400.0     200.0     400.0     300.0     400.0  Card VIIIb-1
48      1                                                                             Card VIIIc
49      3   32    7    3    5    4                                                    Card VIIIa
50         0.0      70.0      10.0     317.5     200.0     317.5     300.0     317.5  Card VIIIb-1
51      2                                                                             Card VIIIc
52      4   32    7    3    5    4                                                    Card VIIIa
53         0.0      70.0      10.0     235.0     200.0     235.0     300.0     235.0  Card VIIIb-1
54      3                                                                             Card VIIIc
55      5   32    7    3    5    4                                                    Card VIIIa
56         0.0      70.0      10.0     152.5     200.0     152.5     300.0     152.5  Card VIIIb-1
57      4                                                                             Card VIIIc
58      6  160    7    3    1    4                                                    Card VIIIa
59         0.0      70.0      10.0     400.0     200.0     400.0     300.0     400.0  Card VIIIb-1
60    161                                                                             Card VIIIc
61      1   32   32    1    1    3                                                    Card IXa
62      1                                                                             Card IXb
63     33                                                                             Card IXc
64               1         5         0         1                                      Card Xa
65         10204Z-DISP NODE 1                                                         Card Xb
66        140104R-DISP NODE 14                                                        Card Xb
67        140204Z-DISP NODE 14                                                        Card Xb
68        230104R-DISP NODE 23                                                        Card Xb
69        230204Z-DISP NODE 23                                                        Card Xb
70            33         4                                                            Card Xd
```

Table 4.18 Input Cards for Sample Problem 6 - Dynamic Loading

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1  REINFORCED CONCRETE SHELL VESSEL - DYNAMIC LOADING                                Card I
 2    128   62    2    4 1200    2    6.0E-5    1    1                              Card II
 3      1    0                                                                      Card III
 4      1   14                                                                      Card IVa-14
 5     2.25E-4       0.2                                           1.0       3.0  Card IVb-14
 6                   8.0       0.0       1.0                13.0       3.0       5.0  Card IVc-14
 7        70.0     4.8E6 7.0833E-4     3.4E3    0.0023     6.8E3       1.0     6.8E3  Card IVd-14
 8         1.0   0.07353      1.15       0.8       4.2   -0.0007    -0.006            Card IVe-14
 9      7.5E-4                 1.0       2.0                                          Card IVg-14
10        70.0     3.1E7  0.002148    6.66E4      0.02    8.23E4                      Card IVh-14
11         4.0                                                                        Card IVi-14
12        12.0      -2.5                                                              Card IVj-14
13         1.0      -3.0      90.0                                                    Card IVj-14
14        12.0       2.5                                                              Card IVj-14
15         1.0       3.0      90.0                                                    Card IVj-14
16      2   11                                                                        Card IVa-11
17      7.5E-4                 0.3                                 1.0       2.0  Card IVb-11
18                   0.1       0.0       0.0                 3.0       2.0       5.0  Card IVc-11
19        70.0     3.0E7  0.001673    5.02E4      0.03     5.6E4                      Card IVd-11
20      1    1     136.0      90.0       0.0     297.0                              Card V
21     14    1     136.0       0.0       0.0     297.0                              Card V
22     15          136.0     280.5                                                  Card V
23     32          136.0       0.0                                                  Card V
24     33    1     132.0      90.0       0.0     297.0                              Card V
25     46    1     132.0       0.0       0.0     297.0                              Card V
26     47          132.0     280.5                                                  Card V
27     64          132.0       0.0                                                  Card V
28     65            0.0       0.0                                                  Card V
29    128            0.0       0.0                                                  Card V
30      1    1    2   66   65                        1   14    1                    Card VI
31     32   33   34   98   97                        2   11    1                    Card VI
32     62   63   64  128  127                        2   11    1                    Card VI
33       10100                                                                        Card VII
34      320110                                                                        Card VII
35      650110                                                                        Card VII
```

Table 4.18 Input Cards for Sample Problem 6 - Dynamic Loading (cont.)

```
               1         2         3         4         5         6         7         8
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
36        960110                                                                        Card VII
37        1   32    1    3    1    2                                                    Card VIIIa
38           0.0    -106.0       1.0    -106.0                                          Card VIIIb-1
39       33                                                                             Card VIIIc
40        1   32   32    1    1    3                                                    Card IXa
41        1                                                                             Card IXb
42       33                                                                             Card IXc
43            10         5         0         1                                          Card Xa
44         10204Z-DISP NODE 1                                                           Card Xb
45        140104R-DISP NODE 14                                                          Card Xb
46        140204Z-DISP NODE 14                                                          Card Xb
47        230104R-DISP NODE 23                                                          Card Xb
48        230204Z-DISP NODE 23                                                          Card Xb
49          1200         4                                                              Card Xd
```

4.6.1 Static Internal Pressurization

For the static internal loading condition with uniform wall temperature, pressurization of the shell model is imposed by monotonically increasing the internal loading in 5 psi increments. It is observed that up to 20 psi the behavior of the vessel is entirely elastic. At internal pressures of 25-30 psi meridional cracking at the base of the vessel begins. The onset of hoop and meridional cracking in the cylinder above 30 psi is followed by hoop and meridional cracking in the dome. Hoop cracking and meridional cracking is practically completed at about 100 psi in the cylinder and dome.

Yielding of the liner is observed to start at about 100 psi at mid-cylinder height, propagates along the cylinder and finally reaches the base at about 110 psi. The yielding of hoop reinforcement at the midheight of the concrete vessel begins at about 110-115 psi. Failure of hoop reinforcement is governed by its strength; this stress limit of 82.3 ksi is reached at an internal pressure of about 125-130 psi. Failure of the hoop reinforcement is found to cause sudden failure of the liner and rupture. The deformed configuration of the vessel, before impending failure, is shown in Fig. 4.15.

Deformation of the vessel is obtained for internal pressures ranging from 5 psi up to 125 psi. Maximum vertical displacement at the dome apex before impending failure of the hoop rebar is 0.12 inches, the corresponding radial and vertical displacements at the vessel springline are 0.64 inches and 0.27 inches. The maximum radial and vertical displacements at cylinder midheight at this load are 2.62 inches and 0.15 inches, respectively, while the respective hoop strain in the liner is 0.02 in/in. The displacements over the complete pressure loading at the cylinder midheight, vessel springline and dome are given in Figs. 4.16 to 4.20.

4.6.2 Thermal Loading and Pressurization

When the structure is subjected to elevated temperature as well as internal pressure, the loadings are performed sequentially. First, the thermal load is applied in 33°F increments on the inside surface of the vessel up to the maximum of 400°F; the external surface is held at 70°F with a linear temperature variation maintained through the thickness. The pressure then is applied in 5 psi increments until failure is reached. Meridional and hoop cracking of the dome and cylinder is observed on the outer surface of the

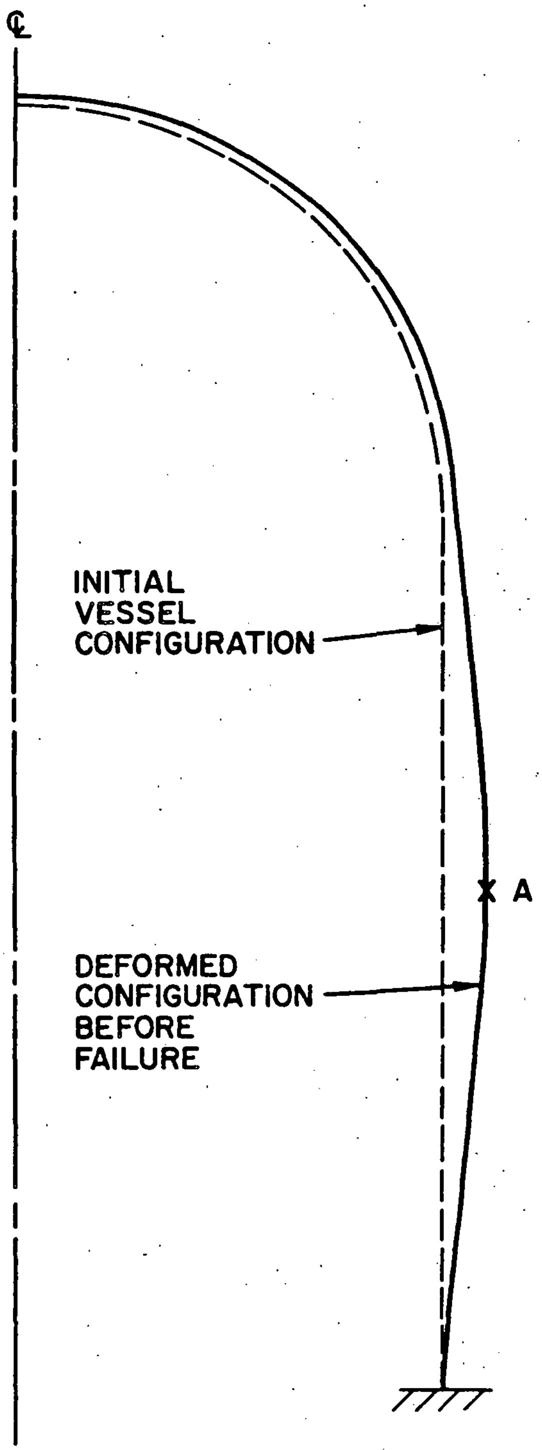


Figure 4.15 Deformation of Vessel at Impending Failure

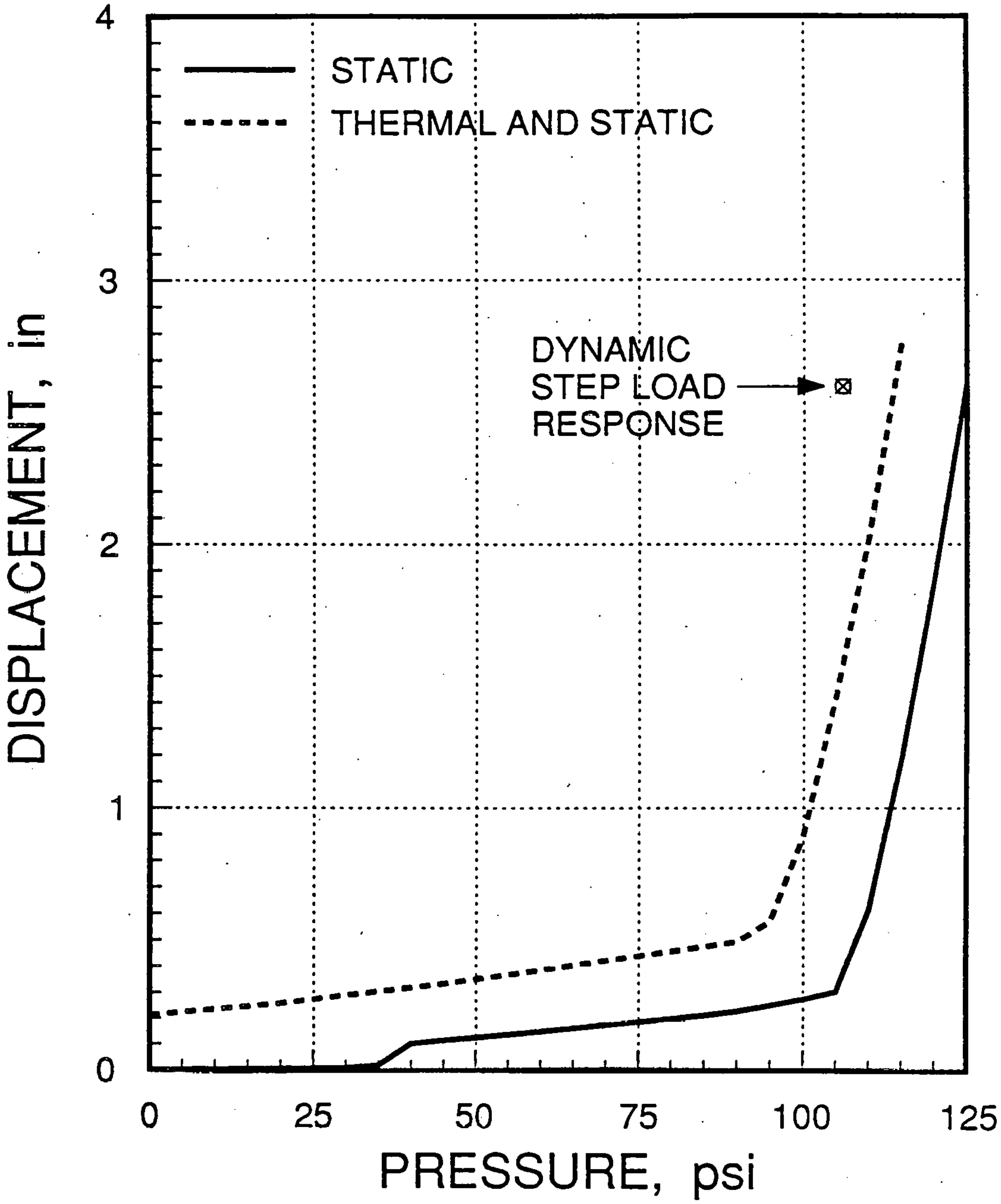


Figure 4.16 Radial Displacement of Liner at Cylinder Midheight

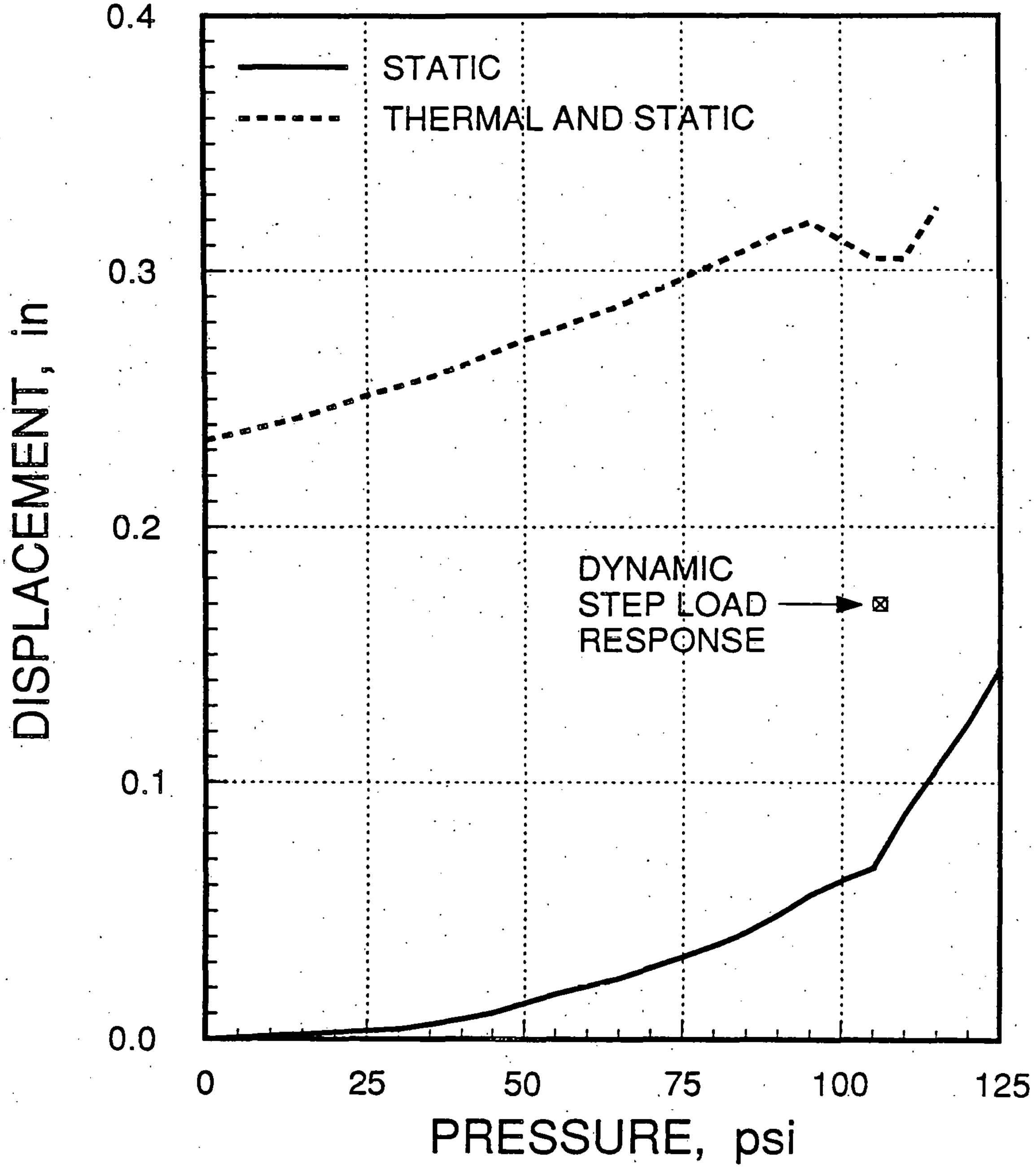


Figure 4.17 Vertical Displacement of Liner at Cylinder Midheight

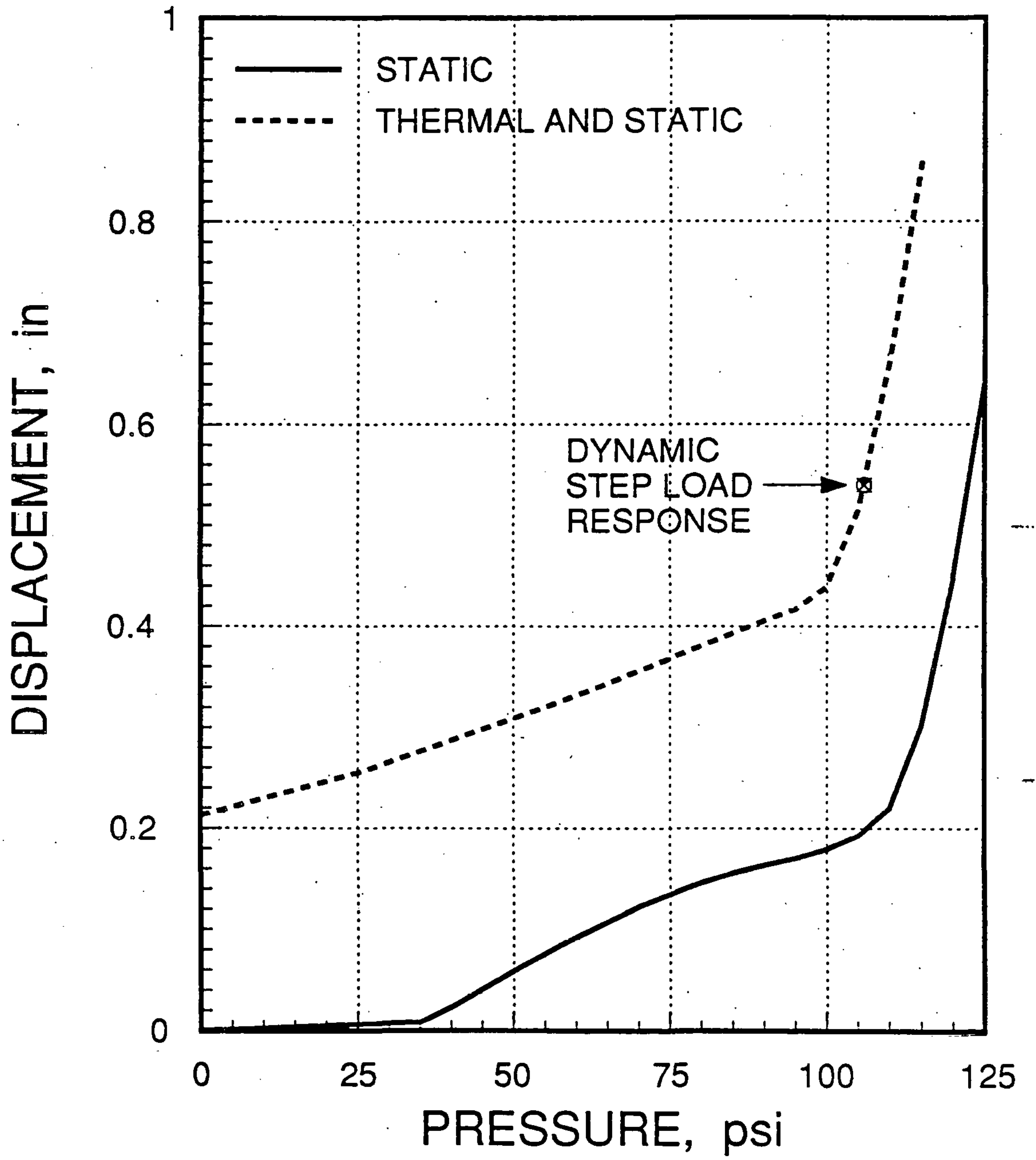


Figure 4.18 Radial Displacement of Liner at Vessel Springline

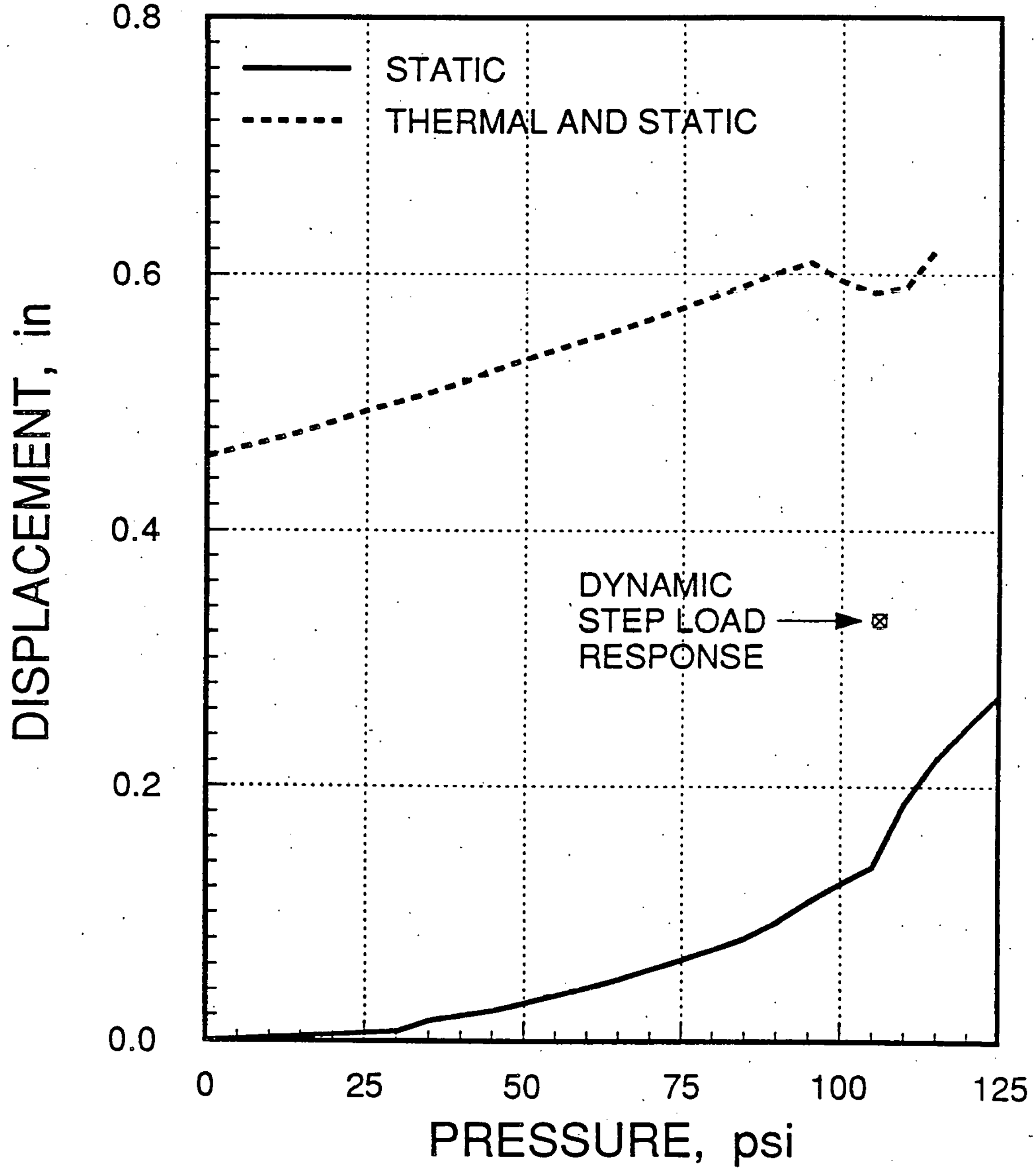


Figure 4.19 Vertical Displacement of Liner at Vessel Springline

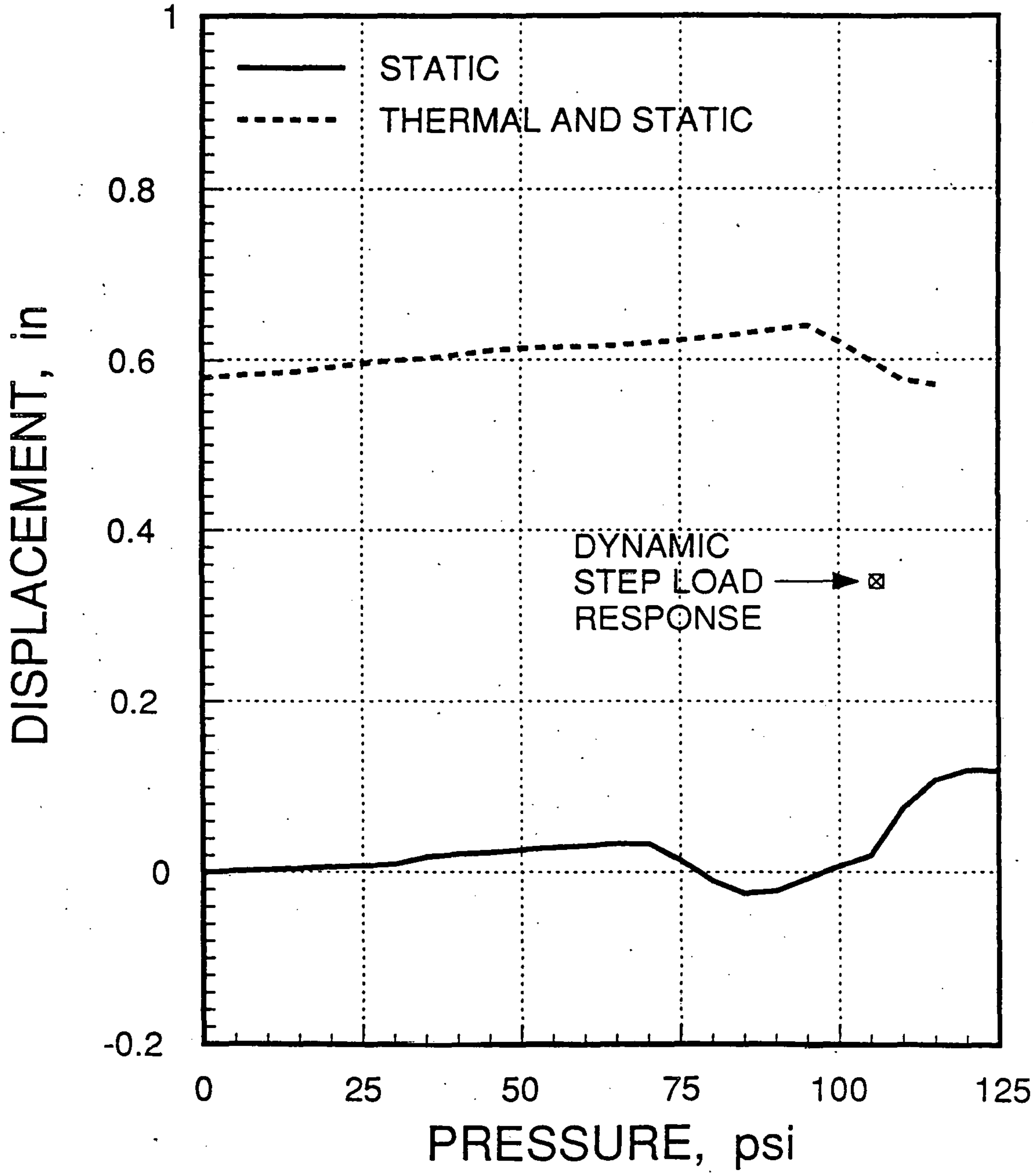


Figure 4.20 Vertical Displacement of Liner at Dome Apex

structure in the first thermal load step. As the thermal load is increased to 400°F, meridional and hoop cracking of the dome and cylinder spreads from the outer surface to about two-thirds of the way through the wall. As the pressure is applied from 5-80 psi, cracking continues in the dome and cylinder. At 100 psi, all the concrete has fully cracked except at the basemat juncture; the concrete in this region is in compression. Yielding of the hoop reinforcement in the cylinder starts at 50 psi. The ultimate strength of the rebar located near the cylinder midheight is exceeded at a pressure of 115-120 psi. This leads to subsequent failure of the liner.

The deformations of the structure are similar to the non-thermal case; there is an increase in magnitude because of thermal expansion and thermal softening effect on the material properties. The maximum vertical displacement of the dome at impending failure in 0.64 inches. The maximum springline radial and vertical displacements are 0.86 inches and 0.62 inches, respectively. At the cylinder midheight, 2.77 inches of radial displacement and 0.32 inches of vertical displacement were calculated. The maximum (hoop) liner strain at the midheight was 0.02 in/in. The displacements over the complete pressure range are given in Figs. 4.16 to 4.20.

4.6.3 Dynamic Loading

The dynamic threshold failure pressure is found by internally loading the structure over a range of step load pressures. The maximum step pressure load that this vessel could withstand before impending failure was 106 psi. A time step of 60 μsec was employed to ensure stability for this loading. The failure for this loading was of the same mode and in the same general location as that given by the static pressure loading, hoop reinforcement failure followed by liner rupture near the cylinder midheight. In general, the displacement field is similar to the static response except at the springline. The maximum vertical displacement of the dome apex at this threshold failure pressure is 0.34 inches which took 13.2 msec to achieve. At the springline, the maximum radial displacement is 0.54 inches at 26.4 msec while the maximum vertical displacement is 0.33 inches in 13.8 msec. The corresponding radial and vertical displacements at the cylinder midheight are 2.6 inches and 0.17 inches which were reached at 27.0 msec and 15.6 msec, respectively. The maximum values for the dynamic step load are indicated in Figs. 4.16 to 4.20.

4.7 Sample Problem 7: Prestressed Concrete Vessel

This example pertains to an internally pressurized prestressed cylindrical container tested by Sozen and Paul (1968). The container simulates the containment of a nuclear reactor vessel. Figure 4.21 identifies the components of the test structure. The analytical model used in the comparison to the experimental data is given in Fig. 4.22. The axisymmetric model consists of 335 concrete continuum elements, 40 prestressed longitudinal bar elements and 41 prestressed circumferential ring elements. A sliding interface with no friction provides for the interaction of the longitudinal prestress bars and the concrete. The material properties of the concrete and steel are given in Table 4.19. The input cards for the mesh are given in Table 4.20.

Prior to internal pressurization, each layer of tendons is prestressed. Each of the longitudinal tendons are prestressed 25200 lbs, each of the circumferential tendons 3487 lbs. The input cards indicate different loads because the tendons are lumped (4.775 bars longitudinally for 1 radian sector and 3 bars circumferentially) at the nodes. The prestress force is applied initially and then allowed to change during the pressurization. Pressurization of the model is imposed by a monotonically increasing internal loading of 50 psi increments to 750 psi. The resulting central deflection of the top slab (point A in Fig. 4.22) and the increase in longitudinal prestress bar force versus internal pressure are given in Figs. 4.23 and 4.24, respectively. These analytical results compare favorably with the experimental data.

Figure 4.25 shows the extent of cracking for the pressure levels of 450, 550, 650 and 750 psi. Cracking initiates at 350 psi and spreads through the upper slab as the pressure increases. With the pressure increase, the corner joint of the wall and slab begins to crack, allowing the upper slab to rotate, causing significant increase in the central deflection of the upper slab.

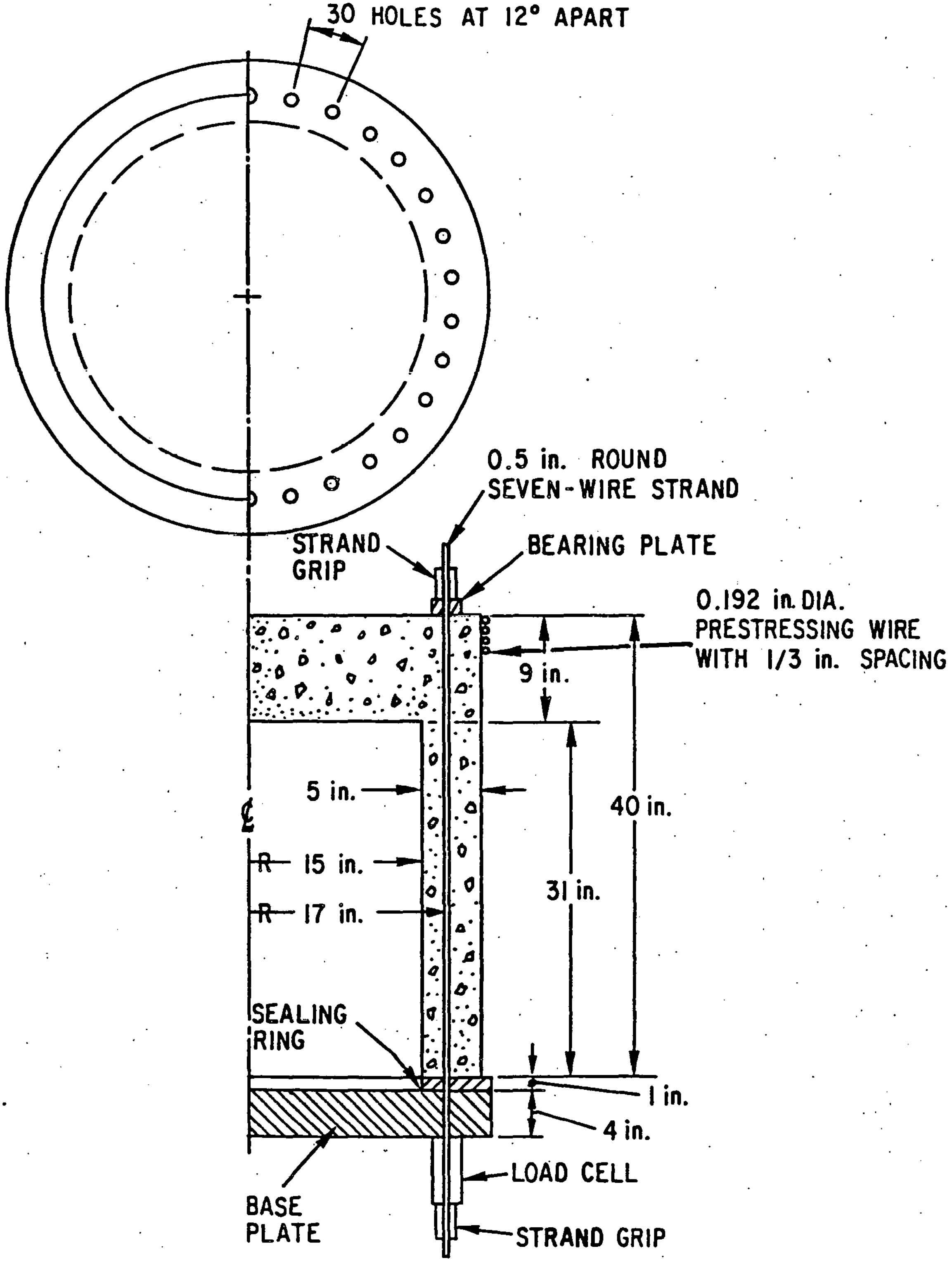


Figure 4.21 Prestressed Concrete Vessel Test Components

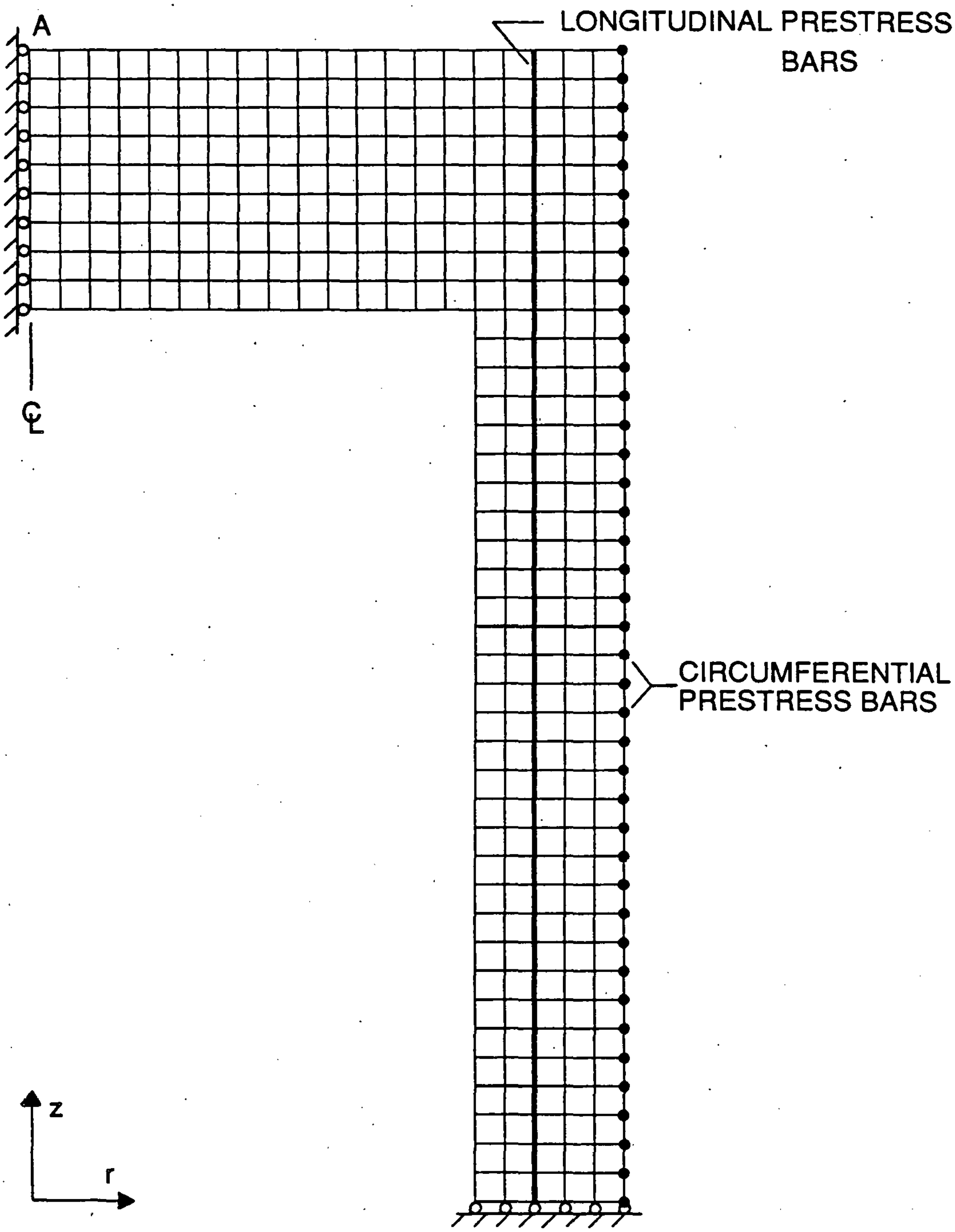


Figure 4.22 Analytical Model of Prestressed Concrete Vessel

Table 4.19 Material Properties for the Prestressed Concrete Vessel (Sample Problem 7)

Concrete Young's modulus	$E = 4.3 \times 10^6$ psi
Concrete Poisson's ratio	$\nu = 0.15$
Concrete compressive strength	$f_c' = 7140$ psi
Concrete tensile strength	$f_t' = 446$ psi
Steel Young's modulus	$E = 2.8 \times 10^7$ psi
Steel yield stress	$\sigma_y = 2.125 \times 10^5$ psi
Steel ultimate stress	$\sigma_u = 2.5 \times 10^5$ psi
Steel ultimate strain	$\varepsilon_u = 0.06$ in/in
Longitudinal prestress force	$f_p = 7.56 \times 10^5$ lbs
Equivalent pressure due to circumferential prestressing	$P_e = 510$ psi

Table 4.20 Input Cards for Sample Problem 7

```
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1   PRESTRESSED CONCRETE CONTAINMENT VESSEL                                           Card I
 2     435  416    4   16   16    2       1.0    1    1              3                 Card II
 3       2    0             90                              15000   10   10    1       Card III
 4       1   13                                                                        Card IVa-13
 5     2.25E-4      0.15                                               1.0       3.0  Card IVb-13
 6                   0.0       0.0       1.0       0.0      13.0       1.0       1.0  Card IVc-13
 7        70.0     4.3E6 0.0008023    3450.0     0.003    7140.0       1.0    7140.0  Card IVd-13
 8         1.0  0.062465      1.15       0.8       4.2   -0.0003    -0.006            Card IVe-13
 9       2   11                                                                        Card IVa-11
10     7.40E-4                                                         1.0       2.0  Card IVb-11
11                0.0445                                     3.0       1.0       1.0  Card IVc-11
12        70.0     2.8E7 0.0075893   2.125E5      0.06     2.5E5                      Card IVd-11
13       3   11                                                                        Card IVa-11
14     7.40E-4                                                         1.0       2.0  Card IVb-11
15                0.0891                                     3.0       1.0       1.0  Card IVc-11
16        70.0     2.8E7 0.0075893   2.125E5      0.06     2.5E5                      Card IVd-11
17       4    1                                                                        Card IVa-1
18     7.40E-4                                                         1.0       2.0  Card IVb-1
19                0.6875                                     1.0       2.0       1.0  Card IVc-1
20        70.0     2.8E7 0.0075893   2.125E5      0.06     2.5E5                      Card IVd-1
21       1           15.0       0.0                                                    Card V
22      41           15.0      40.0                                                    Card V
23      42           16.0       0.0                                                    Card V
24      82           16.0      40.0                                                    Card V
25      83           17.0       0.0                                                    Card V
26     123           17.0      40.0                                                    Card V
27     124           18.0       0.0                                                    Card V
28     164           18.0      40.0                                                    Card V
29     165           19.0       0.0                                                    Card V
30     205           19.0      40.0                                                    Card V
31     206           20.0       0.0                                                    Card V
32     246           20.0      40.0                                                    Card V
33     247            0.0      31.0                                                    Card V
34     261           14.0      31.0                                                    Card V
35     262            0.0      32.0                                                    Card V
```

Table 4.20 Input Cards for Sample Problem 7 (cont.)

```
             1         2         3         4         5         6         7         8
    12345678901234567890123456789012345678901234567890123456789012345678901234567890
36    276           14.0      32.0                                                    Card V
37    277            0.0      33.0                                                    Card V
38    291           14.0      33.0                                                    Card V
39    292            0.0      34.0                                                    Card V
40    306           14.0      34.0                                                    Card V
41    307            0.0      35.0                                                    Card V
42    321           14.0      35.0                                                    Card V
43    322            0.0      36.0                                                    Card V
44    336           14.0      36.0                                                    Card V
45    337            0.0      37.0                                                    Card V
46    351           14.0      37.0                                                    Card V
47    352            0.0      38.0                                                    Card V
48    366           14.0      38.0                                                    Card V
49    367            0.0      39.0                                                    Card V
50    381           14.0      39.0                                                    Card V
51    382            0.0      40.0                                                    Card V
52    396           14.0      40.0                                                    Card V
53    397           17.0       1.0                                                    Card V
54    435           17.0      39.0                                                    Card V
55      1    1   42   43    2                        1   13    1                      Card VI
56     41   42   83   84   43                        1   13    1                      Card VI
57     81   83  124  125   84                        1   13    1                      Card VI
58    121  124  165  166  125                        1   13    1                      Card VI
59    161  165  206  207  166                        1   13    1                      Card VI
60    201  247  248  263  262                        1   13    1                      Card VI
61    215  261   32   33  276                        1   13    1                      Card VI
62    216  262  263  278  277                        1   13    1                      Card VI
63    230  276   33   34  291                        1   13    1                      Card VI
64    231  277  278  293  292                        1   13    1                      Card VI
65    245  291   34   35  306                        1   13    1                      Card VI
66    246  292  293  308  307                        1   13    1                      Card VI
67    260  306   35   36  321                        1   13    1                      Card VI
68    261  307  308  323  322                        1   13    1                      Card VI
69    275  321   36   37  336                        1   13    1                      Card VI
70    276  322  323  338  337                        1   13    1                      Card VI
```

Table 4.20 Input Cards for Sample Problem 7 (cont.)

```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
 71      290  336   37   38  351                        1   13    1                      Card VI
 72      291  337  338  353  352                        1   13    1                      Card VI
 73      305  351   38   39  366                        1   13    1                      Card VI
 74      306  352  353  368  367                        1   13    1                      Card VI
 75      320  366   39   40  381                        1   13    1                      Card VI
 76      321  367  368  383  382                        1   13    1                      Card VI
 77      335  381   40   41  396                        1   13    1                      Card VI
 78      336  206  206                             2    2   11    1                      Card VI
 79      337  207  207                             3    3   11    1                      Card VI
 80      376  246  246                             2    2   11    1                      Card VI
 81      377   83  397                             4    4    1    1                      Card VI
 82      378  397  398                             4    4    1    1                      Card VI
 83      416  435  123                             4    4    1    1                      Card VI
 84           10010                                                                      Card VII
 85          420010                                                                      Card VII
 86          830010                                                                      Card VII
 87         1240010                                                                      Card VII
 88         1650010                                                                      Card VII
 89         2060010                                                                      Card VII
 90         2470100                                                                      Card VII
 91         2620100                                                                      Card VII
 92         2770100                                                                      Card VII
 93         2920100                                                                      Card VII
 94         3070100                                                                      Card VII
 95         3220100                                                                      Card VII
 96         3370100                                                                      Card VII
 97         3520100                                                                      Card VII
 98         3670100                                                                      Card VII
 99         3820100                                                                      Card VII
100        1   47    1    2    0    2                                                    Card VIIIa
101           1.0       0.0     101.0    5000.0                                          Card VIIIb-1
102        1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16  Card VIIIc
103       17   18   19   20   21   22   23   24   25   26   27   28   29   30   31   32  Card VIIIc
104      261  260  259  258  257  256  255  254  253  252  251  250  249  248  247       Card VIIIc
105        2    1   11    2    0    3                                                    Card VIIIa
```

Table 4.20 Input Cards for Sample Problem 7 (cont.)

```
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
106         1.0    5230.8       2.0       0.0     100.0       0.0                      Card VIIIb-1
107    336                                                                             Card VIIIc
108      3    1   11    2    0    3                                                    Card VIIIa
109         1.0   10461.5       2.0       0.0     100.0       0.0                      Card VIIIb-1
110    337                                                                             Card VIIIc
111      4    1   11    2    0    3                                                    Card VIIIa
112         1.0  120321.0       2.0       0.0     100.0       0.0                      Card VIIIb-1
113    377                                                                             Card VIIIc
114      1   39   39    1    1    0                                                    Card IXa
115     84                                                                             Card IXb
116    397                                                                             Card IXc
117           1         1         2         0                                          Card Xa
118     3820204Y-DISP NODE 382                                                         Card Xb
119     4160034PRESTRESS IN ELE 416                                                    Card Xc
120     4210024INTERNAL ENERGY                                                         Card Xc
```

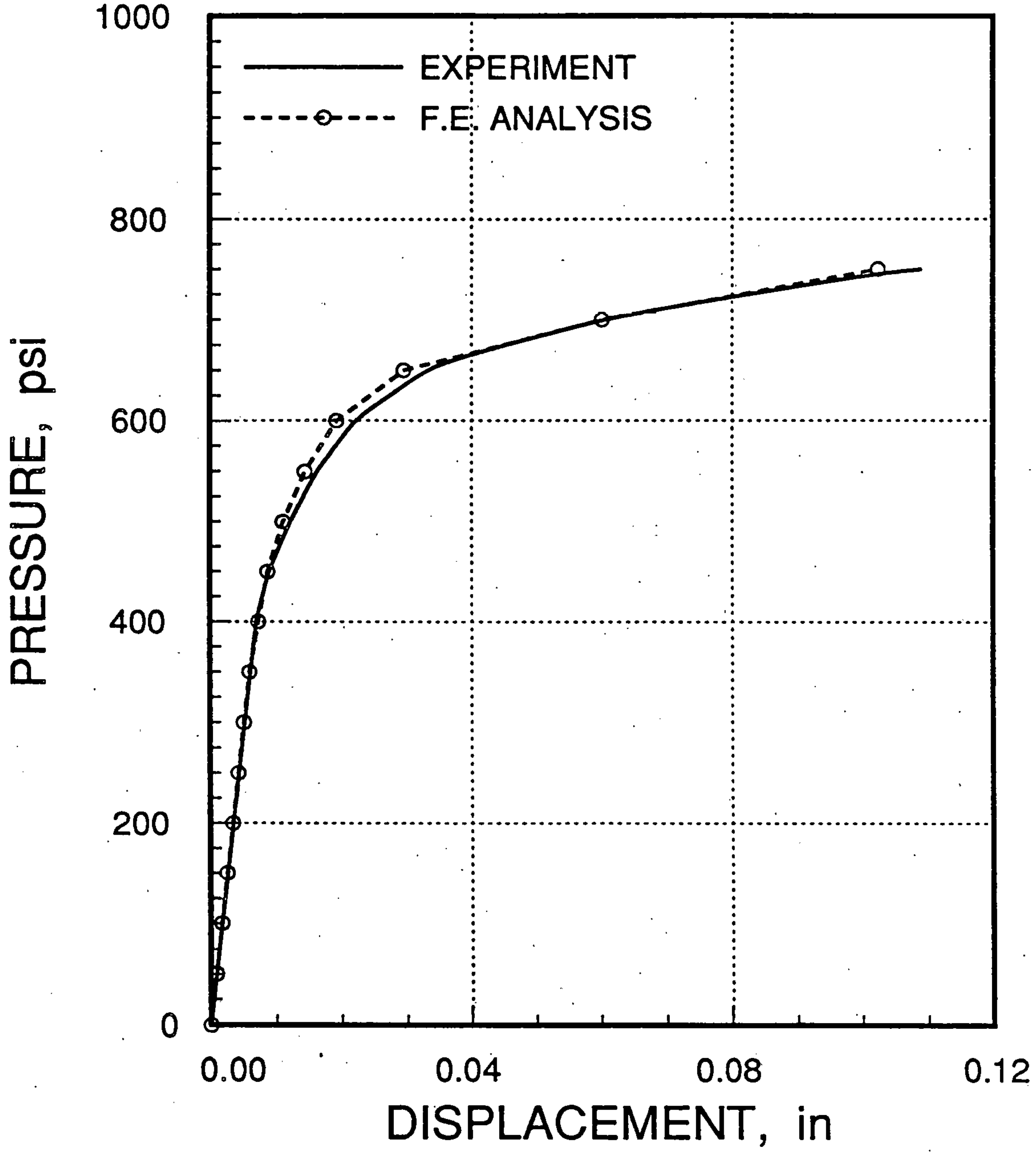


Figure 4.23 Central Deflection of the Top Slab

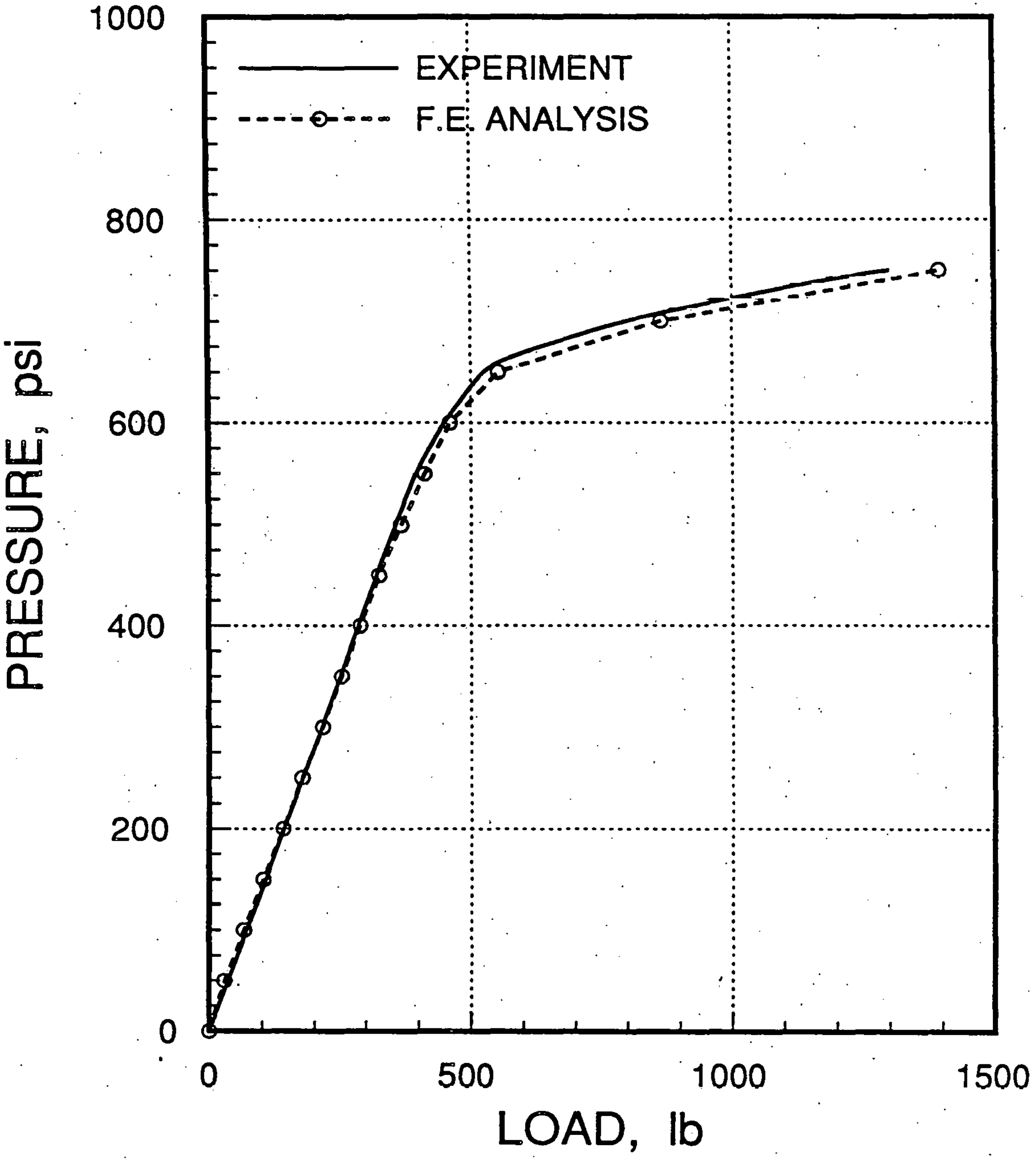


Figure 4.24 Increase in Longitudinal Prestress Bar Force

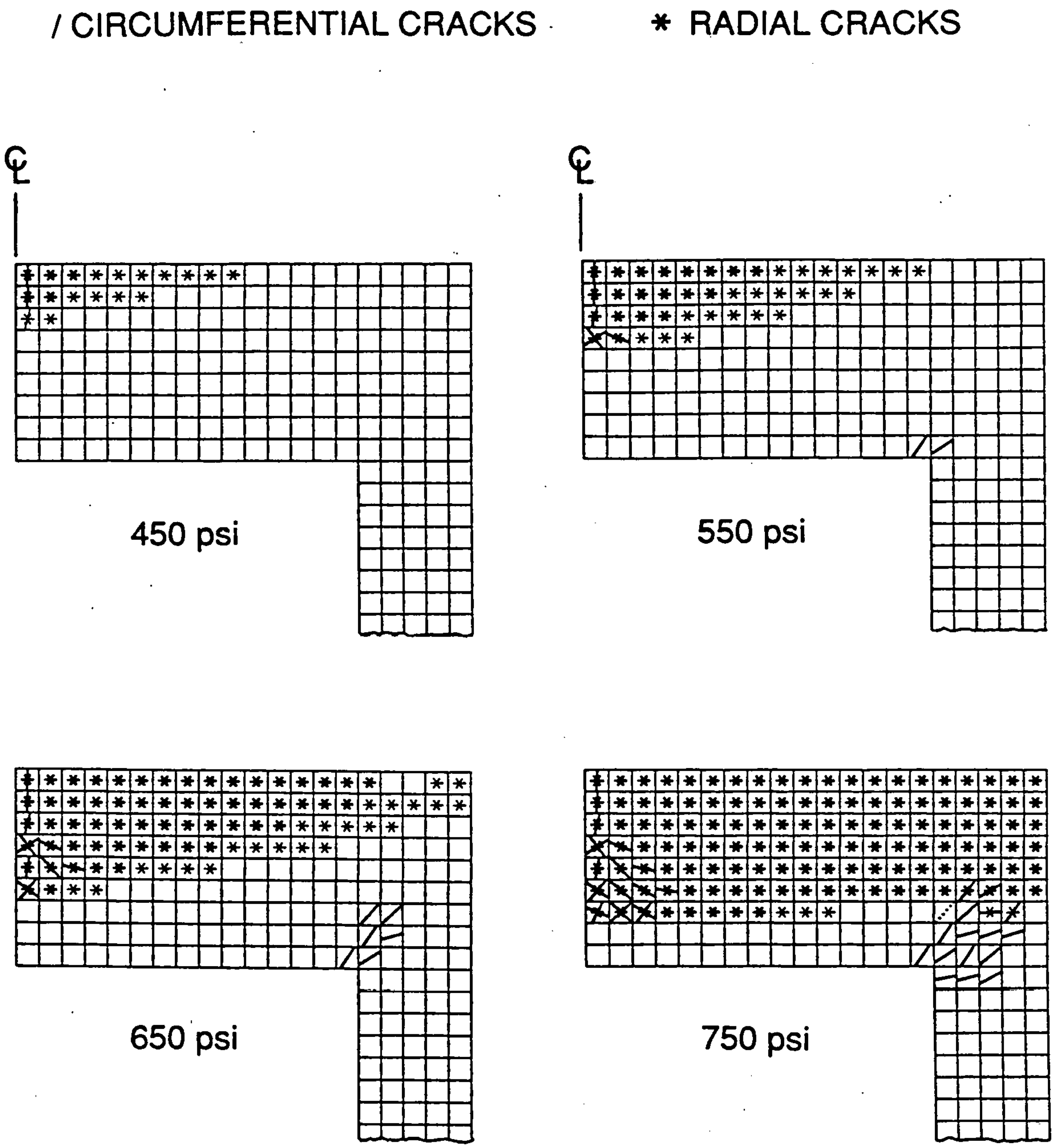


Figure 4.25 Extent of Cracking of Prestressed Concrete Vessel Model

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