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2D BEAM-COLUMN ELEMENT (TYPE 5-PARALLEL ELEMENT THEORY) FOR THE ANSR-II PROGRAM

by

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GRAHAM H. POWELL
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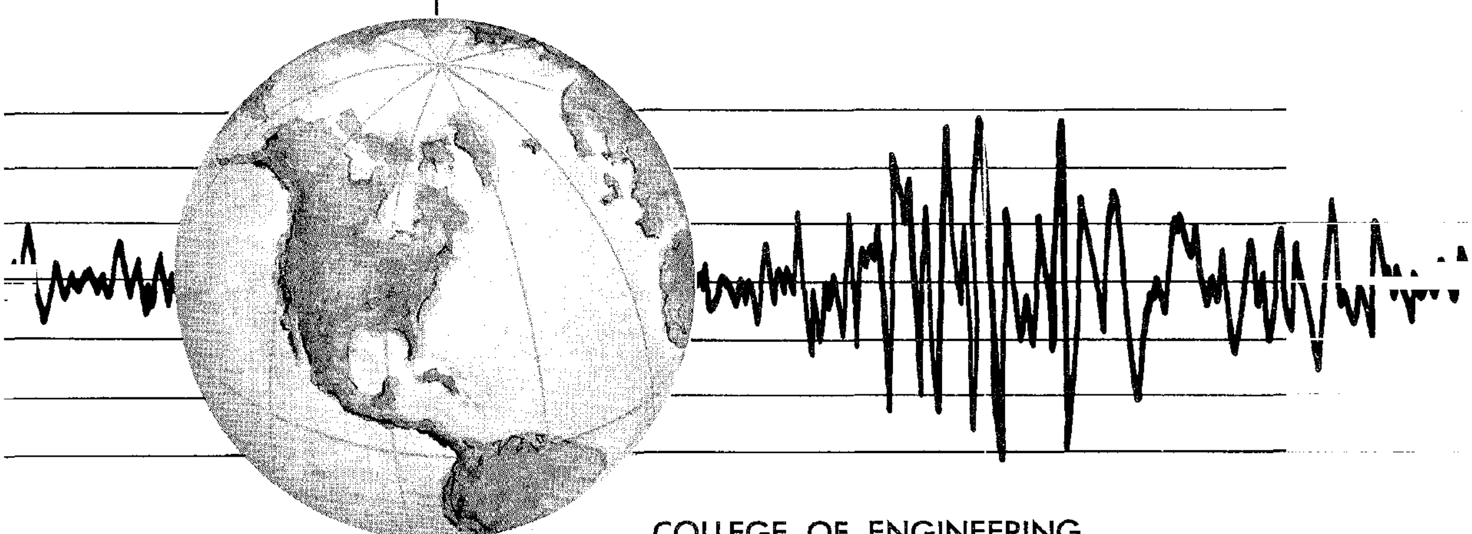

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2D BEAM-COLUMN ELEMENT

(TYPE 5 - PARALLEL ELEMENT THEORY)

FOR THE ANSR-II PROGRAM

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Report to
National Science Foundation

Report No. UCB/EERC - 79/30
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ABSTRACT

This report describes a two-dimensional inelastic beam-column element developed for the ANSR-II program. The report contains a description of the element characteristics and the computer program user's guide.

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TABLE OF CONTENTS

1. INTRODUCTION

This report describes a two-dimensional beam-column element for the ANSR-II program [1]. The element has the following features:

(1) Arbitrary 3D orientation of element, but stiffness and strength defined in a local 2D coordinate system (in-plane bending). Out-of-plane bending not explicitly considered.

(2) Yielding in concentrated plastic hinges at the element ends.

(3) Plastic hinge formation governed by bending moment (in principal plane) and axial force.

(4) Bilinear action-deformation relationships.

(5) Beam type, steel column type, or reinforced concrete column type yield surface.

(6) Different yield strengths at two ends if desired.

(7) Rigid joint zones if desired.

(8) Initial forces in the element if desired.

(9) Rigid diaphragm slaving at any one or both ends of the element if desired.

(10) Shear deformations may be included or ignored.

(11) For dynamic analysis, damping proportional to initial elastic stiffness and/or current tangent stiffness.

(12) P-delta effect may be considered ("second order" analysis), but not true large displacements.

This report contains a description of the element and the element user's guide.

2. TWO DIMENSIONAL BEAM-COLUMN ELEMENT

2.1 GENERAL CHARACTERISTICS

Beam column elements may be arbitrarily oriented in the global XYZ plane. If the slaving feature is to be used, the Y axis must be vertical.

Each element must be assigned an axial stiffness plus a major axis flexural stiffness. Torsional and minor axis flexural stiffnesses may also be specified if necessary, as explained in Section 2.4. Elements of variable cross section can be considered by specifying appropriate flexural stiffness coefficients. Flexural shear deformations and the effects of eccentric end connections can be taken into account.

Yielding may take place only in concentrated plastic hinges at the element ends. Hinge formation is affected by the axial force and major axis bending moment only. That is, an element may be placed in a three-dimensional frame, but its yield mechanism is only two-dimensional, in the plane of major axis bending. The yield moments may be specified to be different at the two element ends, and for positive and negative bending. The interaction between axial force and moment in producing yield is taken into account approximately.

Strain hardening is approximated by assuming that the element consists of elastic and elasto-plastic components in parallel. With this type of strain hardening idealization, if the bending moment in the element is constant, and if the element is of uniform strength, then the moment-rotation relationship for the element will have the same shape as its moment-curvature relationship (Fig. 2.1a). This follows because curvature and rotation in this case are directly proportional. If, however, the bending moment or strength vary, then the curvatures and rotations are no longer proportional, and the moment-rotation and moment-curvature variations may be quite different (Fig. 2.1b). With the parallel component procedure, a moment-rotation relationship is, in effect, being specified. Care must be taken in relating this to a moment-curvature relationship.

If static load analyses are carried out separately (i.e., outside the ANSR program), the results of these analyses may be included by specifying appropriate initial axial forces and bending moments in the elements. The P-delta effect can be considered if desired.

2.2 ELEMENT DEFORMATIONS

The beam-column element has three primary modes of deformation, namely (a) axial extension and (b) flexural rotations in the major plane at ends i and j. The transformation relating increments of element deformation to increments of nodal displacement (Fig. 2.2) is

$$\underline{dv}_p = \underline{a}_p \, \underline{dr} \tag{2.1}$$

in which $\underline{dv}_p^T = (dv_1, dv_2, dv_3)$; $\underline{dr}^T = (dr_1, dr_2, \ldots , dr_{12})$; and the transformation $\underline{a}_p$ is well known.

The element also has three secondary modes of deformation, which may have to be considered for reasons explained in Section 2.4. These consist of minor axis flexural deformations at ends i and j, and an angle of torsional twist. Again, the transformation from displacements to deformations is well known (Fig. 2.2), and can be expressed as

$$\underline{dv}_s = \underline{a}_s \, \underline{dr} \tag{2.2}$$

in which $\underline{dv}_s^T = (dv_4, dv_5, dv_6)$.

It is assumed that these secondary deformations are elastic, and that they do not interact with the primary deformations in producing plastic hinges.

A plastic hinge forms when the moment in the elasto-plastic component of the element reaches its yield moment. A hinge is then introduced into this component, the elastic component remaining unchanged. The measure of flexural plastic deformation is the plastic hinge rotation.

For any increments of total flexural rotation, dv_2 and dv_3, the corresponding increments of plastic hinge rotation, $d\theta_{p2}$ and $d\theta_{p3}$, are given by

$$\begin{Bmatrix} d\theta_{p2} \\ d\theta_{p3} \end{Bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{Bmatrix} dv_2 \\ dv_3 \end{Bmatrix} \tag{2.3}$$

in which A, B, C, and D are as given in Table 2.1. Unloading occurs at a hinge when the increment in hinge rotation is opposite in sign to the bending moment.

Inelastic axial deformations are assumed not to occur in beam-column elements of this type, to simplify the problem of interaction between axial and flexural deformations after yield. Only an approximate procedure for considering interaction effects is included, as explained in the following section. This procedure is not strictly consistent, but is believed to be reasonable for most practical applications.

2.3 INTERACTION SURFACES

Yield interaction surfaces of three types may be specified, as follows:

(1) Beam type (shape code = 1, Fig. 2.3a). This type of surface should be specified where axial forces are small or are ignored. Yielding is affected by bending moment only.

(2) Steel column type (shape code = 2, Fig. 2.3b). This type of surface is intended for use with steel I-columns.

(3) Concrete column type (shape code = 3, Fig. 2.3c). This type of surface is intended for use with concrete columns.

For any combination of axial force and bending moment within a yield surface, the cross section is assumed to be elastic. If the force-moment combination lies on or outside the surface, a plastic hinge is introduced. Combinations outside the yield surface are permitted only temporarily, being compensated for by applying corrective loads in the succeeding load step or iteration.

This procedure is not strictly correct because the axial and flexural deformations interact after yield, and it is therefore wrong to assume that the flexural stiffness changes but the axial stiffness remains unchanged. However, this procedure is believed to be reasonable for practical analyses of buildings.

If a force-moment combination goes from the elastic range to beyond the yield surface in any load step or iteration, an equilibrium correction is made as shown in Fig. 2.4a. Also, because the axial stiffness is assumed toremain unchanged, the force-moment combination at a plastic hinge will subsequently move away from the yield surface if yielding continues, as shown in Fig. 2.4b. An equilibrium correction, as shown, is therefore made in each succeeding step or iteration.

The axial force in an element with a column-type interaction surface can, in reality, never exceed the yield value for zero moment. However, because of the computational procedure being used, axial forces in excess of yield can be computed. For axial forces in excess of yield, the yield moments are assumedto be zero. The printed results from the program should be examined carefully and interpreted with caution. If axial forces approaching or exceeding yield are computed for a column, severe column damage is probably implied.

2.4 ELEMENT STIFFNESS

The element is considered as the sum of an inelastic component and an elastic component in the major plane of bending, plus a further elastic component providingtorsional and minor axis flexural stiffnesses. This third component is needed to avoid singular stiffness matrices in certain circumstances.

The element actions and deformations are shown in Fig. 2.2. The axial stiffness is constant, and is given by

$$dS_1 = \frac{EA}{L} dv_1 \tag{2.4}$$

in which E = elastic modulus, and A = effective cross sectional area. The primary elastic flexural stiffness is given by

$$\begin{Bmatrix} dS_2 \\ dS_3 \end{Bmatrix} = \frac{EI}{L} \begin{bmatrix} k_{ii} & k_{ij} \\ k_{ij} & k_{jj} \end{bmatrix} \begin{Bmatrix} dv_2 \\ dv_3 \end{Bmatrix} \tag{2.5}$$

in which I = reference moment of inertia; and k_{ii}, k_{ij}, k_{jj} are coefficients which depend on the cross section variation. For a uniform element, I = actual moment of inertia, $k_{ii} = k_{jj} = 4$, and $k_{ij} = 2$. The coefficients must be specified by the program user, and may, if desired, account for such effects as shear deformations and nonrigid end connections as well as cross section variations.

After one or more hinges form, the coefficients for the elasto-plastic component change to k'_{ii}, k'_{ij}, and k'_{jj}, as follows:

$$k'_{ii} = k_{ii}(1-A) - k_{ij}\,C \qquad (2.6)$$

$$k'_{ij} = k_{ij}(1-D) - k_{ii}\,B \qquad (2.7)$$

$$k'_{jj} = k_{jj}(1-D) - k_{ij}\,B \qquad (2.8)$$

in which A, B, C, and D are defined in Table 2.1.

If desired, effective flexural shear areas may be specified. The program then modifies the flexural stiffness to account for the additional shear deformations.

The minor axis flexural stiffness is obtained by multiplying the primary elastic stiffness by a user-specified factor, f. The torsional deformation is related to torque by

$$dS_6 = \frac{GJ}{L}\,dv_6 \qquad (2.9)$$

in which it is assumed that G = 0.4E and

$$J = f(k_{ii} + k_{jj})I/8 \qquad (2.10)$$

in which k_{ii} and k_{jj} are the primary flexural stiffness factors, after any modification for shear deformations.

The primary and secondary actions are related to their respective deformations by

$$\underline{dS}_p = \underset{\sim}{k}_p \, \underline{dv}_p \tag{2.11}$$

and

$$\underline{dS}_s = \underset{\sim}{k}_s \, \underline{dv}_s \tag{2.12}$$

2.5 P-DELTA EFFECT

Even for small displacements, changes in the shape of a structure can have a significant effect (the P-delta effect) on the equilibrium of the structure. This effect can be accounted for by adding a geometric stiffness to the element elastic or elasto-plastic stiffness, and by accounting for change of shape in the calculation of the resisting force for the element.

The geometric stiffness assumed for the element is that for a truss bar in three dimensions, which depends on the axial force only. The geometric stiffness is changed each time the elasto-plastic stiffness changes, using the current axial force, but is otherwise assumed to remain constant.

The effect of including the geometric stiffness is to account approximately (linearized or "second order" approximation) for large displacement effects. A corresponding correction is included in the state determination calculations, by modifying the resisting forces exerted by the element on the nodes at its ends. The modification adds shear forces to the nodes, based on the element axial force and its chord rotation (Δ/h).

2.6 END ECCENTRICITY

Plastic hinges in frames and coupled frame-shear wall structures will form near the faces of the joints rather than at the theoretical joint centerlines. This effect can be approximated by postulating rigid, infinitely strong connecting links between the nodes and the element ends, as shown in Fig. 2.6. The displacement transformation relating the increments of node displacements, $\underline{dr}_n$, to increments of displacement at the element ends is easily established, and can be written as

$$\underline{dr} = \underline{a}_e \, \underline{dr}_n \tag{2.13}$$

2.7 GLOBAL STIFFNESS

The element stiffness, K, relating global actions and displacements is obtained as

$$\underline{K} = \underline{a}_e^T \, \underline{a}_p^T \, \underline{K}_p \, \underline{a}_p \, \underline{a}_e + \underline{a}_s \, \underline{K}_s \, \underline{a}_s^T + \underline{K}_G \tag{2.14}$$

where $\underline{K}_G$ is included only if the P-delta effect is to be considered. For simplicity, the secondary element is assumed to join the nodes i and j directly, without end eccentricities. The geometric stiffness is also formulated for a member connecting nodes i and j directly.

2.8 RIGID FLOOR DIAPHRAGMS

A frequently made assumption in the analysis of tall buildings is that each floor diaphragm is rigid in its own plane. To introduce this assumption, a "master" node at the center of mass of each floor may be specified, as shown in Fig. 2.7. Each master node has only three degrees of freedom as shown, which are the displacements of the diaphragm horizontally as a rigid body. If any beam-column member is connected to a diaphragm, its stiffness must be formulated partly in terms of these "master" displacements and partly in terms of displacements which are not affected by the rigid diaphragm assumption.

The displacement transformation relating the diaphragm displacements, $\underline{dr}_d$, to the displacements at a slaved node is as follows:

$$\begin{Bmatrix} dr_{n1} \\ dr_{n3} \\ dr_{n5} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & d_Z \\ 0 & 1 & -d_X \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} dr_X \\ dr_Y \\ dr_\theta \end{Bmatrix} \tag{2.15}$$

or

$$\underline{dr}_{ns} = \underline{a}_d \, \underline{dr}_d \tag{2.16}$$

The slaved displacements at element nodes i and j can be expressed in terms of the displacements at the "master" node (or nodes). The corresponding coefficients of $\underline{K}$ (Eq. 2.14) are transformed to account for the slaving. The resulting element stiffness matrix is assembled in terms of the three master degrees of freedom plus the three local degrees of freedom dr_{n2}, dr_{n4}, and dr_{n6} at each node, which are not affected by slaving.

2.9 INITIAL FORCES

For structures in which static analyses are carried out separately, (i.e., outside the ANSR program), initial primary member forces may be specified. The sign convention for these forces is as shown in Fig. 2.5. These forces are not converted to loads on the nodes of the structure, but simply used to initialize the element end actions. For this reason, initial forces need not constitute a set of actions in equilibrium. The only effects they have on the behavior of the system are (a) to influence the onset of plasticity and (b) to affect the geometric stiffnesses.

Primary initial forces are defined as standard patterns. Each element can be identified with a standard pattern, and in addition a multiplication factor for scaling the standard pattern may be specified.

2.10 RESULTS OUTPUT

The following results are printed at the specified output intervals, during static and dynamic analyses, for those elements for which element force histories are requested.

(1) yield code at each end of element: Zero indicates the element end is elastic, and 1 that a plastic hinge has formed.

(2) axial force, bending moment and shear force acting on each end, with the sign convention shown in Fig. 2.5.

(3) current plastic hinge rotations at each end. The sign convention is the same as for primary flexural actions and deformations.

(4) accumulated positive and negative plastic hinge rotations up to the current time. These values are accumulated as shown in Fig. 2.8.

The maximum positive and negative values of axial force, bending moment, shear force, and plastic hinge rotation, with their times of occurrence, are printed at the time intervals requested for envelopes. The accumulated positive and negative plastic hinge rotations are also printed.

3. USER'S GUIDE

2D BEAM COLUMN ELEMENT (TYPE 5)

3.1 CONTROL INFORMATION

Two cards.

3.1(a) First Card

COLUMNS	NOTE	NAME	DATA
5(I)		NGR	Element group indicator. Punch 5.
6 - 10(I)	(1)	NELS	Number of elements in group.
11 - 15(I)		MFST	Element number of first element in group. Default = 1.
16 - 25(F)		DKO	Initial stiffness damping factor, β_o.
26 - 35(F)		DKT	Tangent stiffness damping factor, β_T.
41 - 80(A)		GRHED	Optional group heading.

3.1(b) Second Card

COLUMNS	NOTE	NAME	DATA
1 - 5(I)		NMBT	Number of different element stiffness types (max. 35). Default = 1.
6 - 10(I)		NECC	Number of different end eccentricity types (max. 15). Default = zero.
11 - 15(I)		NSURF	Number of different yield interaction surfaces for cross sections (max. 40). Default = 1.
16 - 20(I)		NINT	Number of different initial force patterns (max. 30). Default = zero.

3.2 STIFFNESS TYPES

NMBT cards.

COLUMNS	NOTE	NAME	DATA
1 - 5(I)			Stiffness type number, in sequence beginning with 1.
6 - 15(F)			Young's modulus of elasticity.
16 - 25(F)			Strain hardening modulus, as a proportion of Young's modulus.
26 - 35(F)			Average cross-sectional area.
36 - 45(F)			Reference moment of inertia.
46 - 50(F)	(2)		Flexural stiffness factor k_{ii}.
51 - 55(F)			Flexural stiffness factor k_{jj}.
56 - 60(F)			Flexural stiffness factor k_{ij}.
61 - 70(F)			Effective shear area. Default or zero = no shear deformation.
71 - 75(F)			Poisson's ratio for calculating shear modulus. Default = zero.
76 - 80(F)	(3)		Factor by which major axis bending stiffness is multiplied to give minor axis bending stiffness. Torsional stiffness is also obtained from this factor. Default = zero (zero torsional and minor axis bending stiffnesses).

3.3 END ECCENTRICITY TYPES

NECC cards.

COLUMNS	NOTE	NAME	DATA
1 - 5(I)	(4)		End eccentricity type number, in sequence beginning with 1.
6 - 15(F)			X_i = X eccentricity at end i.
16 - 25(F)			X_j = X eccentricity at end j.
26 - 35(F)			Y_i = Y eccentricity at end i.

3.3 END ECCENTRICITY TYPES (Continued)

COLUMNS	NOTE	NAME	DATA
36 - 45(F)			Y_j = Y eccentricity at end j.
46 - 55(F)			Z_i = Z eccentricity at end i.
56 - 65(F)			Z_j = Z eccentricity at end j.

3.4 CROSS SECTION YIELD INTERACTION SURFACES

NSURF cards.

COLUMNS	NOTE	NAME	DATA
1 - 5(I)			Yield surface number, in sequence beginning with 1.
10(I)			Surface shape code. (a) 1: Beam type, without P-M interaction. (b) 2: Steel column type. (c) 3: Reinforced concrete column type.
11 - 20(F)	(5)		Positive (sagging) yield moment, M_{y+} .
21 - 30(F)			Negative (hogging) yield moment, M_{y-} .
31 - 40(F)			Compression yield force, P_{yc}. (Shape code = 2 or 3 only.)
41 - 50(F)			Tension yield force, P_{yt}. (Shape code = 2 or 3 only.)
51 - 55(F)			M-coordinate of balance point A. as a proportion of M_{y+} (shape code = 2 or 3 only).
56 - 60(F)			P-coordinate of balance point A, as a proportion of P_{yc} (shape code = 2 or 3 only).
61 - 65(F)			M-coordinate of balance point B, as a proportion of M_{y-} (shape code = 2 or 3 only).
66 - 70(F)			P-coordinate of balance point B, as a proportion of P_{yc} (shape code = 2 or 3 only).

3.5 INITIAL ELEMENT FORCE PATTERNS

NINT cards.

COLUMNS	NOTE	NAME	DATA
1 - 5(I)	(6)		Pattern number, in sequence beginning with 1.
6 - 15(F)			Initial axial force, F_i.
16 - 25(F)			Initial shear force, V_i.
26 - 35(F)			Initial moment, M_i.
36 - 45(F)			Initial axial force, F_j.
46 - 55(F)			Initial shear force, V_j.
56 - 65(F)			Initial moment, M_j.

3.6 ELEMENT DATA GENERATION

As many cards as needed to generate all elements in group.

COLUMNS	NOTE	NAME	DATA
1 - 5(I)	(7)	MEL	Element number, or number of first element in a sequentially numbered series of elements to be generated by this card.
6 - 10(I)		NODI	Node number I.
11 - 15(I)		NODJ	Node number J.
16 - 20(I)	(8)	NODK	Number of a third node, K, not collinear with NODI and NODJ, which defines the local xy plane. No default.
21 - 25(I)		INC	Node number increment for element generation. Default = 1.
26 - 30(I)	(9)	NSI	Number of node (diaphragm node) to which end I is slaved. Default = no slaving.
31 - 35(I)		NSJ	Number of node (diaphragm node) to which end J is slaved. Default = no slaving.
36 - 40(I)		IMBT	Stiffness type number. No default.
41 - 45(I)		IECC	End eccentricity type number. Default = no end eccentricity.

3.6 ELEMENT DATA GENERATION (Continued)

COLUMNS	NOTE	NAME	DATA
46 - 50(I)		KSFI	Yield surface number at end I. No default.
51 - 55(I)		KSFJ	Yield surface number at end J. No default.
56 - 60(I)	(10)	KGEOM	Small displacements code. (a) Blank or zero = small displacements. (b) 1 = large displacements ("second order" analysis, with P-delta effect).
61 - 65(I)		KTHO	Response output code. (a) Blank or zero = no response printout. (b) 1 = response printout required.
66 - 70(I)		INIT	Initial force pattern number. Default = no initial forces
71 - 75(F)		SFAC	Scale factor to be applied to initial forces. Default = no initial forces.

3.7 USER'S GUIDE NOTES

NOTE (1) The elements in the group are numbered sequentially, starting with MFST (i.e. MFST, MFST+1,...,MFST+NELS-1).

NOTE (2) Stiffness factors k_{ii}, k_{jj} and k_{ij} can be used, if desired, to account for effects such as cross section variation and nonrigid end connections. For a prismatic element these factors are $k_{ii} = k_{jj} = 4$ and $k_{ij} = 2$. These factors may also account for shear deformations, in which case it is not necessary to input an effective shear area.

NOTE (3) Refer to Section 2.4 for explanation on minor axis stiffnesses.

NOTE (4) All eccentricities are measured from the node to the element end (Fig. 2.6), positive in the positive coordinate directions.

NOTE (5) Refer to Fig. 2.3 for interaction surface types and for positive direction of yield moment.

NOTE (6) See Fig. 2.5 for the positive directions of initial element forces. Refer to Section 2.9 for a description of the effects of initial element forces.

NOTE (7) Cards must be input in order of increasing element number. Cards for the first and the last elements must be included (that is data for these two elements cannot be generated.)

Cards may be provided for all elements, in which case each card specifies the data for one element, and the generation option is not used. Alternatively, cards for a series of elements may be omitted, in which case data for the missing elements is generated as follows:

(a) All missing elements are assigned the same node "k" (NODK), slave nodes (NSI and NSJ), stiffness type, end eccentricity type, yield surface types, initial force pattern type, and codes for small displacements and response output, as for the element preceding the missing series of elements.

(b) The node numbers I and J for each missing element are obtained by adding the increment (INC) to the node numbers of the preceding element. That is,

NODI (N) = NODI (N-1) + INC

NODJ (N) = NODJ (N-1) + INC

Node increment (INC) is the value specified with the element preceding the missing series of elements.

3.7 USER'S GUIDE NOTES (Continued)

NOTE (8) Refer to Fig. 2.5

NOTE (9) Refer to Fig. 2.9

NOTE (10) Refer to Section 2.5.

TABLE 2.1

COEFFICIENTS FOR PLASTIC HINGE ROTATIONS

Yield Condition	A	B	C	D
Elastic ends	0	0	0	0
Plastic hinge at end i only	1	k_{ij}/k_{ii}	0	0
Plastic hinge at end j only	0	0	k_{ij}/k_{jj}	1
Plastic hinges at both ends i and j	1	0	0	1

Coefficients k_{ii}, k_{ij}, and k_{jj} are defined by Eq. 2.5.

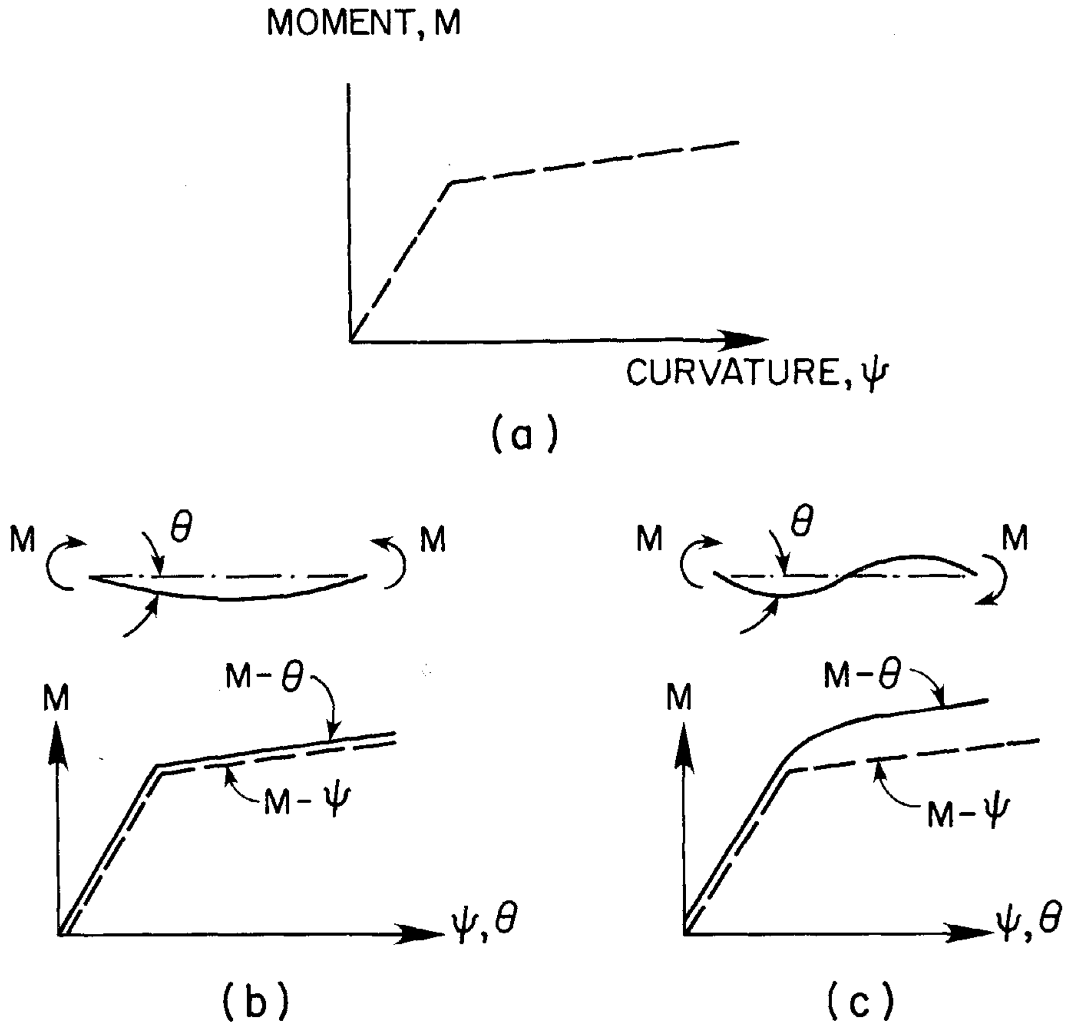


FIG. 2.1 MOMENT-CURVATURE AND MOMENT-ROTATION RELATIONSHIP

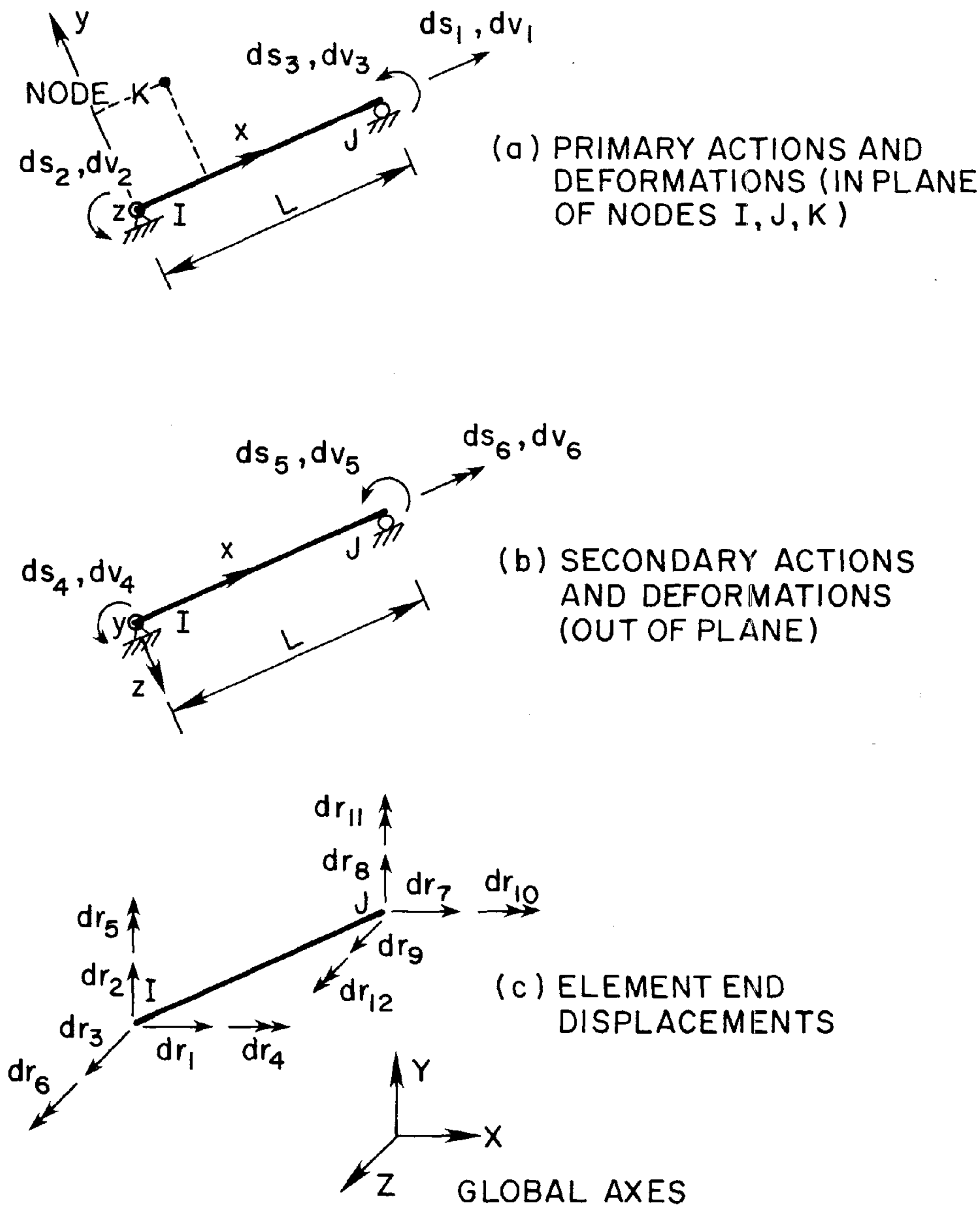
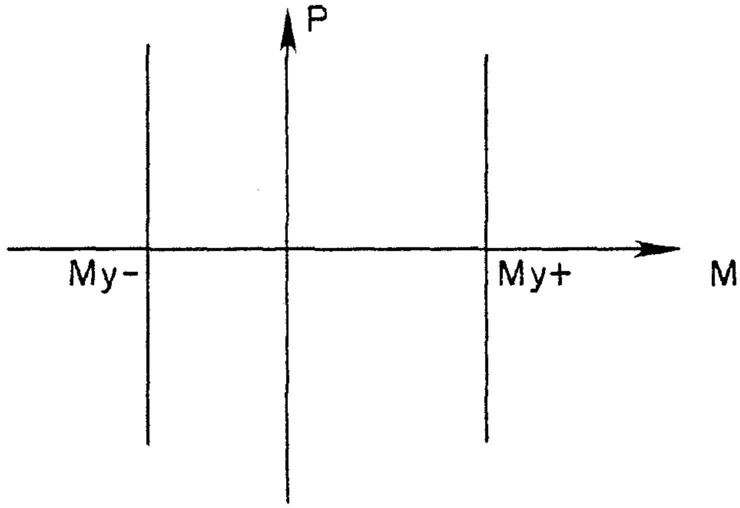
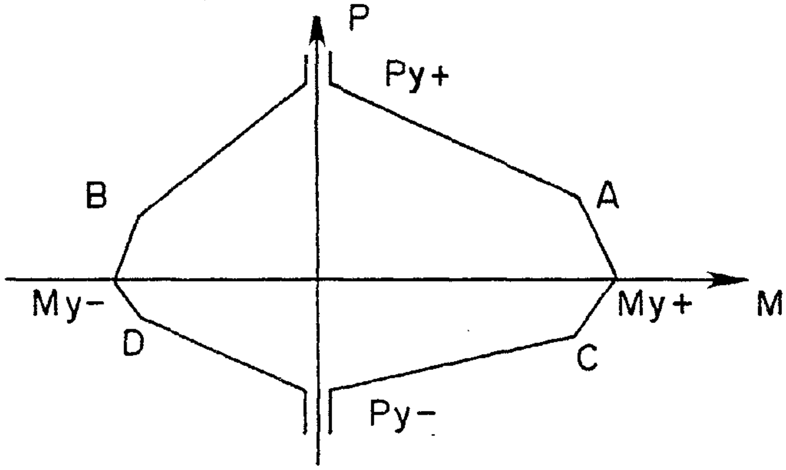


FIG. 2.2 DEFORMATIONS AND DISPLACEMENTS



(a) SHAPE CODE = 1



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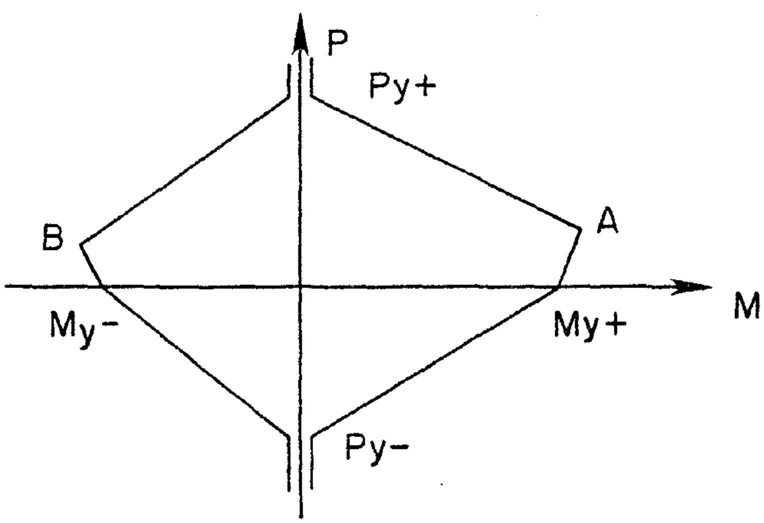


(c) SHAPE CODE = 3

FIG. 2.3 YIELD INTERACTION SURFACES

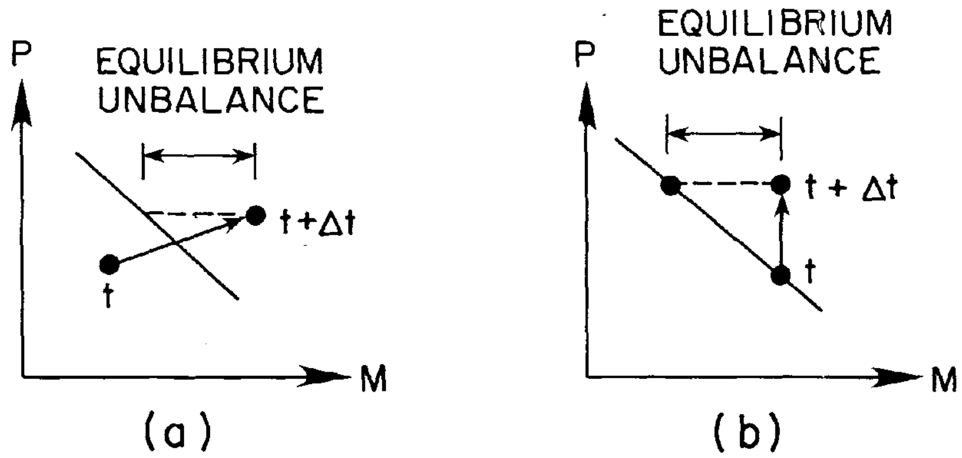


FIG. 2.4 EQUILIBRIUM CORRECTION FOR YIELD SURFACE OVERSHOOT

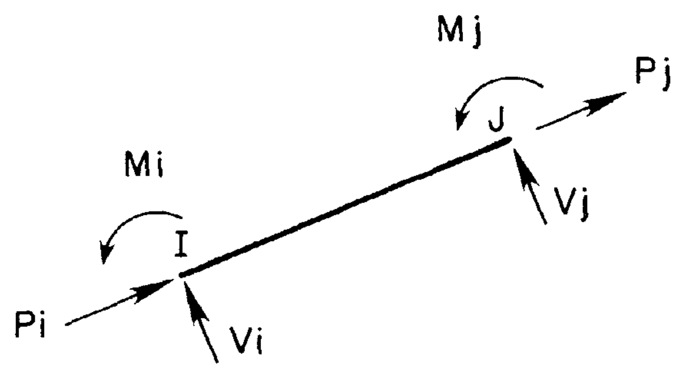


FIG. 2.5 POSITIVE DIRECTION FOR INITIAL FORCES AND OUTPUT RESULTS

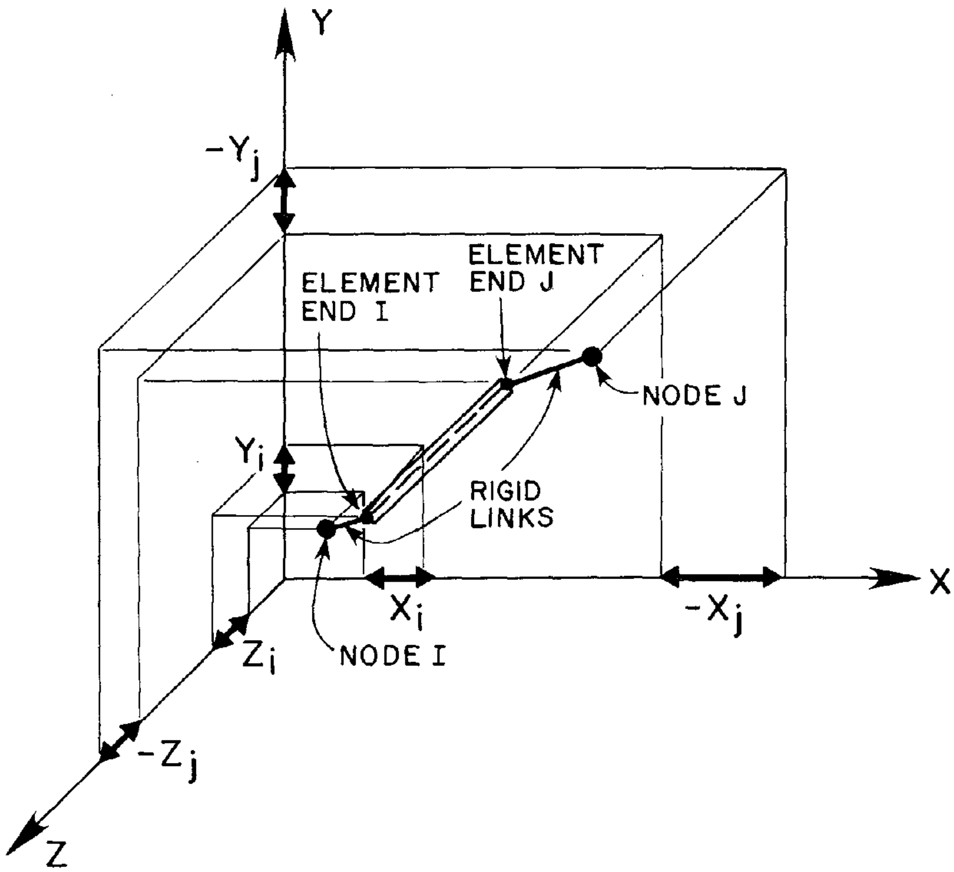


FIG. 2.6 END ECCENTRICITIES

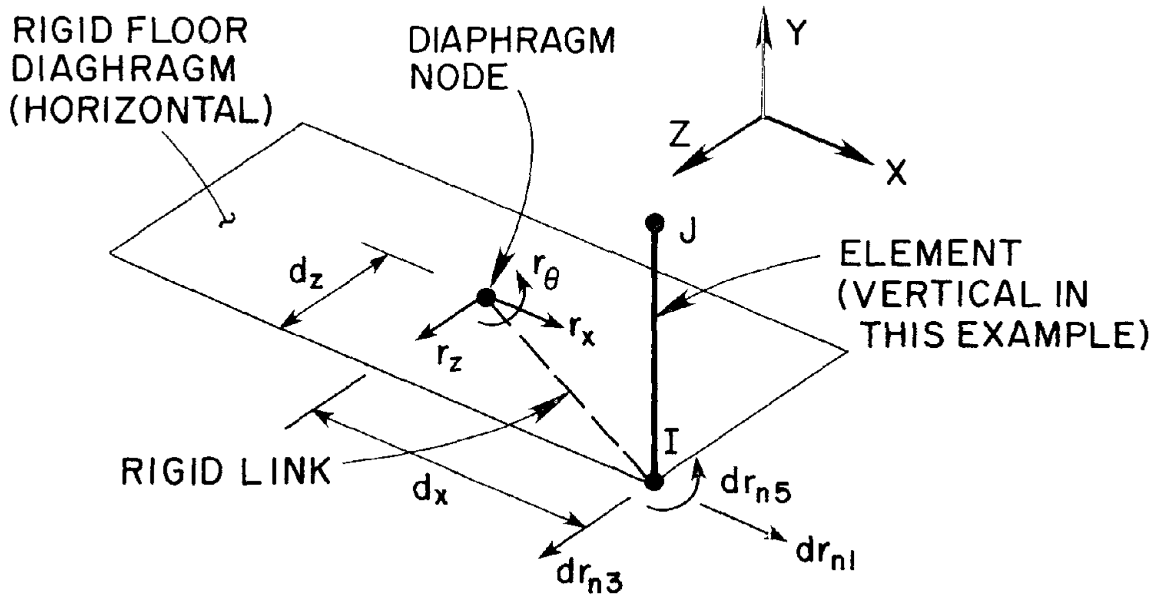
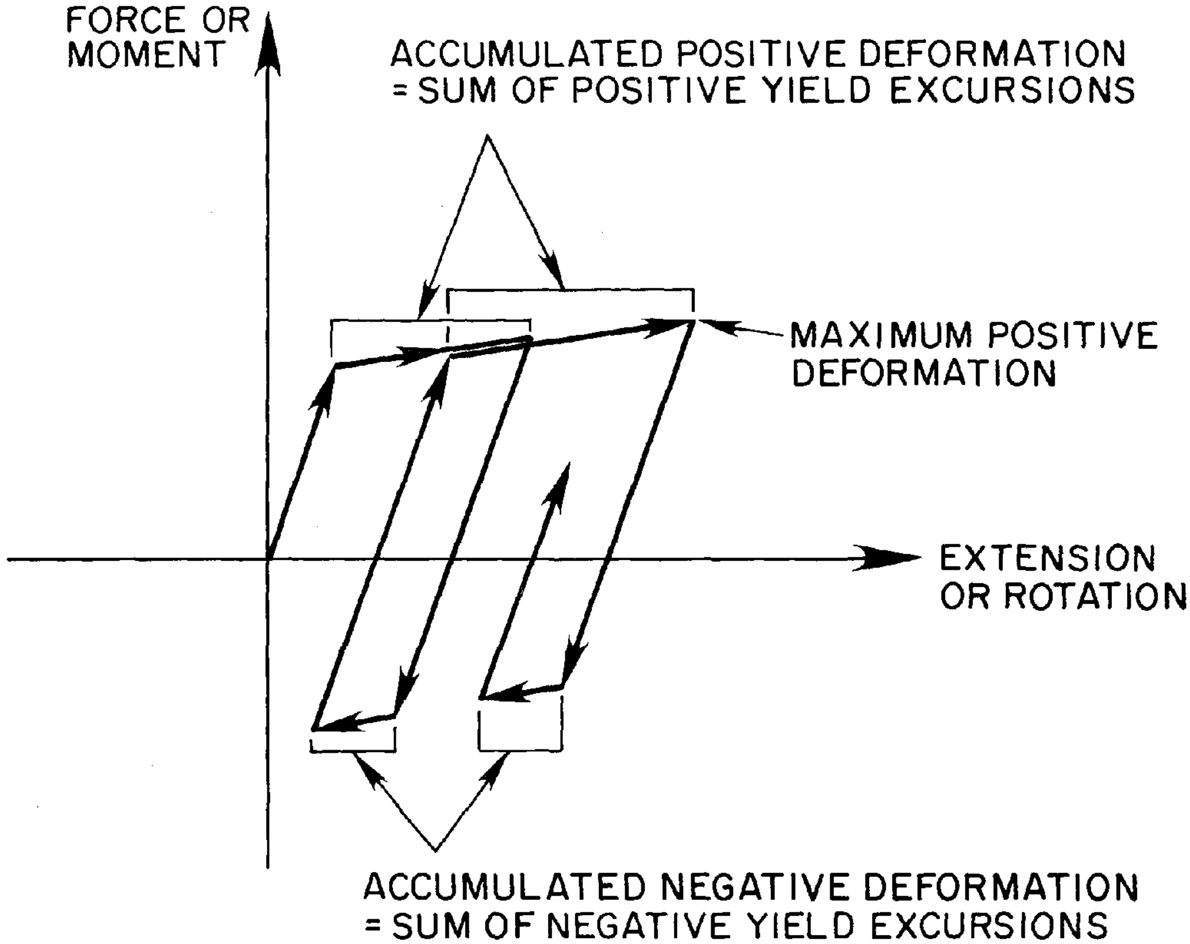


FIG. 2.7 RIGID FLOOR DIAPHRAGM MODELLING



NOTE THAT MAXIMUM NEGATIVE DEFORMATION IS ZERO, ALTHOUGH ACCUMULATED NEGATIVE DEFORMATION IS NOT ZERO

FIG. 2.8 PROCEDURE FOR COMPUTATION OF ACCUMULATED PLASTIC DEFORMATIONS

REFERENCE

1. Mondkar, D.P. and Powell, G.H., "ANSR-II, Analysis of Nonlinear Structural Response, User's Manual", Report No. UCB/EERC-79/17, Earthquake Engineering Research Center, University of California, Berkeley (July 1979).