GAP-FRICTION ELEMENT (TYPE 5)

FOR THE ANSR-II PROGRAM

by

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ABSTRACT

This report describes a 3D gap-friction element developed for the ANSR-II program.

The report contains a description of the element properties, the element theory, and a computer program user's guide.

ACKNOWLEDGEMENT

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1. INTRODUCTION

This report describes a three-dimensional gap-friction element developed for the ANSR-II code [1]. The element has the following features:

(1) Arbitrary orientation of bearing plane in 3D space.

(2) Zero stiffness perpendicular and tangential to bearing plane when gap is open.

(3) Trilinear inelastic force-deformation relationship for deformation perpendicular to bearing plane following gap closure.

(4) Frictional behavior tangential to bearing plane when gap is closed, with constant friction coefficent.

(5) Bearing plane may translate in space (for example, to represent earthquake excitation), but its orientation must remain fixed.

(6) Internal viscous damping is zero.

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

2. ELEMENT PROPERTIES

2.1 GENERAL CHARACTERISTICS

The element resists deformation normal and tangential to a specified bearing plane. The bearing plane may be arbitrarily oriented in space.

The element consists of two components, namely, (a) a bearing component acting normal to the bearing plane and (b) a friction component acting parallel to the bearing plane.

The element is connected to the structure at node N (Fig. 1). The bearing plane is defined by three nodes, I, N, and J, as shown. The normal component is oriented along the local z-axis, normal to the bearing plane. The local x-axis lies in the bearing plane, directed from node J to node N. The local y-axis, also in the bearing plane, is perpendicular to the z-x plane.

If motions of the bearing plane are to be permitted, a fourth node, M, must be defined. The element then connects nodes N and M, and the translation of M defines the motion of the plane. Node M may be part of a deformable structure. Nodes M and N must have identical coordinates (i.e. the element must be of zero length). If node M is not specified, the bearing plane will be fixed in space (in effect, zero displacement for node M). The element deformations are the relative displacements of nodes N and M.

The force-deformation relationship for the normal component is shown in Fig. 2. The relationship for the tangential component is as shown in Fig. 3. For a force less than that required to cause slip, the behavior is elastic with stiffness K_f. When the force equals the slip value (normal component force multiplied by the friction coefficient), slip takes place. If the force in the normal component is zero (i.e. open gap), both the normal and tangential components have zero stiffnesses.

2.2 SENSITIVITY

If the stiffness following gap closure is large, large unbalanced forces may develop, and the solution may be inaccurate or numerically unstable. Both the normal and tangential stiffnesses should be made as small as possible, and the results should be studied for signs of instability. It may be necessary to use a very small time step.

3. THEORY AND COMPUTATIONAL PROCEDURE

3.1 ELEMENT STIFFNESS

The element has three deformations, namely, (a) deformation v_z along the local z-axis of the normal component and (b) deformations v_x and v_y along the local x and y axes, respectively, of the tangential component. The increments in element deformations are related to the increments in nodal displacements, as follows (Fig. 4):

$$\underline{dv} = \underline{T}\,\underline{dr} \qquad \text{if node } M = 0 \tag{1a}$$

or

$$\underline{dv} = [\underline{T} \;\; -\underline{T}]\,\underline{dr} \qquad \text{if node } M \neq 0 \tag{1b}$$

in which

$$\underline{dv}^T = (dv_x, dv_y, dv_z) \tag{2}$$

$$\underline{dr}^T = (dr_{XN}, dr_{YN}, dr_{ZN}) \quad \text{if node } M = 0 \tag{3a}$$

or

$$\underline{dr}^T = (dr_{XN}, dr_{YN}, dr_{ZN}, dr_{XM}, dr_{YM}, dr_{ZM}) \quad \text{if node } M \neq 0 \tag{3b}$$

The transformation matrix $\underline{T}$ contains the direction cosines of the local x-y-z axes with respect to the global X-Y-Z axes.

The tangent force-deformation relationship for the normal component is

$$dF_z = K_z\, dv_z \tag{4}$$

in which dF_z = increment in force and K_z = tangent stiffness of the normal component. The tangent stiffness, K_z, may be equal to zero, K1, K2, or K3, depending on the state of the normal component (Fig. 2).

The force states required to produce slip of the tangential component are defined by a "slip circle" in the bearing plane (Fig. 5). The radius, F_s, of the circle is equal to the normal component force multiplied by the friction coefficient.

If the local x and y forces, F_x and F_y, in the tangential component are such that $\sqrt{(F_x)^2 + (F_y)^2}$ is less than F_s, the behavior of the tangential component is elastic. The tangent stiffness of this component is then given by

$$\begin{Bmatrix} dF_x \\ dF_y \end{Bmatrix} = \begin{bmatrix} K_f & 0 \\ 0 & K_f \end{bmatrix} \begin{Bmatrix} dv_x \\ dv_y \end{Bmatrix} \tag{5}$$

This tangent stiffness assumes two springs, each with stiffness K_f, along the local x and y axes in the bearing plane (Fig. 5a).

If the forces F_x and F_y are such that $\sqrt{(F_x)^2 + (F_y)^2}$ is equal to F_s, the tangential component is assumed to be slipping along the radial direction of the slip circle (Fig. 5b). The tangent stiffness of the component is then given by

$$\begin{Bmatrix} dF_r \\ dF_t \end{Bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & K_f \end{bmatrix} \begin{Bmatrix} dv_r \\ dv_t \end{Bmatrix} \tag{6}$$

in which r and t are the radial and tangential directions, respectively, at the point on the slip circle (Fig. 5b). This tangent stiffness assumes a spring with stiffness K_f along the tangent to the slip circle. The tangent stiffness in the local x and y axes is thus given by

$$\begin{bmatrix} dF_x \\ dF_y \end{bmatrix} = K_f \begin{bmatrix} \sin^2\alpha & -\sin\alpha\cos\alpha \\ -\sin\alpha\cos\alpha & \cos^2\alpha \end{bmatrix} \begin{Bmatrix} dv_x \\ dv_y \end{Bmatrix}$$

$$= \begin{bmatrix} K_{xx} & K_{xy} \\ K_{xy} & K_{yy} \end{bmatrix} \begin{Bmatrix} dv_x \\ dv_y \end{Bmatrix} \quad (7)$$

in which $\cos\alpha = F_x/F_s$ and $\sin\alpha = F_y/F_s$.

The tangent stiffness matrix of the complete element, $\underset{\sim}{K}_{xyz}$, is obtained by combining Eqs. (4) and (5) or Eqs. (4) and (7), giving

$$\underset{\sim}{K}_{xyz} = \begin{bmatrix} K_f & 0 & 0 \\ 0 & K_f & 0 \\ 0 & 0 & K_z \end{bmatrix} \text{ or } \underset{\sim}{K}_{xyz} = \begin{bmatrix} K_{xx} & K_{xy} & 0 \\ K_{xy} & K_{yy} & 0 \\ 0 & 0 & K_z \end{bmatrix} \quad (8)$$

The tangent stiffness matrix in global axes is then given by

$$\underset{\sim}{K}_{XYZ} = \underset{\sim}{T}^T \underset{\sim}{K}_{xyz} \underset{\sim}{T} \qquad \text{if node M = 0} \quad (9a)$$

or by

$$\underset{\sim}{K}_{XYZ} = [\underset{\sim}{T} \; -\underset{\sim}{T}]^T \underset{\sim}{K}_{xyz} [\underset{\sim}{T} \; -\underset{\sim}{T}] \qquad \text{if node M} \neq 0 \quad (9b)$$

3.2 STATE DETERMINATION

Increments of element deformation are computed using Eq. (1a) or (1b). The force increment in the normal component is then obtained by following the force-deformation relationship shown in Fig. 2. The computation of force increments for the tangential component is more complex because during any load or time step the state of force can change in many ways and because the slip circle may change in size.

As an example, consider Fig. 6. At the beginning of the step, let the tangential force be at point A, within the slip circle, so that the state is elastic. The radius of the slip circle is equal to the normal force at the beginning of the step multiplied by the friction coefficient. Assuming linear behavior within the step, let the tangential force at the end of the step be at point B. This point is outside the slip circle, which is incorrect. If the tangential deformations are assumed to increase proportionately, and if the slip circle is assumed not to change, point C on path AB can be found such that the tangential force state lies on the slip circle. For the remainder of the deformation increment, slip occurs, with zero restraint along the radial direction at any time. The tangential force increment for this remainder of the deformation increment is computed using Eq. (7). In general, the coefficients in Eq. (7) will not be constant throughout the step. In the computer program, however, constant coefficients are assumed and a force state at D is found. This point lies outside the circle. Further, in computing the forces at point D, it has been assumed that the slip circle does not change during the step, which is not generally correct. The slip circle corresponding to the normal force at the end of the step might, for example, be as shown in Fig. 6. The forces at point D must be corrected to correspond to the new slip circle. If the force state at D is within the new slip circle, the forces are left unchanged and the new state is set to be elastic. If the force state is outside the new slip circle, the forces are scaled radially, as shown, to give point E on the slip circle, and the new state is set to be slipping.

If substantial deformations occur within a single load or time step, this procedure may be inaccurate and may lead to large unbalanced loads.

3.3 ANGLE TOLERANCE FOR STIFFNESS REFORMULATION

If slip continues to occur in the tangential component over several load steps, the element stiffness will generally change continuously, because angle α (Fig. 7 and Eq. (7)) will generally change. If the change in α is small, the change in stiffness can be ignored, and computer costs for reforming the stiffness can be saved. In the computer program, an option is provided for the user to specify a tolerance for the angle α. If a nonzero tolerance is specified, the element stiffness is reformed only when the change in state is such that the angle between the current state and that at which the stiffness was last reformed exceeds the tolerance.

4. RESULTS OUTPUT

The following response results are printed at the specified output intervals in static and dynamic analyses for those gap-friction elements for which the response results are requested.

(a) Element number.

(b) Node numbers N and M.

(c) Yield code for the normal component (Fig. 2).

(d) Normal component deformation.

(e) Normal component force.

(f) Slip code for the tangential component. Zero indicates that the component is elastic; one indicates that it is slipping.

(g) Local x-axis and y-axis deformations of the tangential component.

(h) Local x-axis and y-axis forces of the tangential component.

The results envelopes consist of the following:

(a) Element number.

(b) Node numbers N and M.

(c) Maximum positive and negative values of the normal component deformation and force, and the times at which these maxima occur.

(d) Maximum positive and negative values of the resultant tangential component deformation and force, and the times at which these maxima occur.

5. USER'S GUIDE

3D GAP-FRICTION ELEMENT (TYPE 7)

5.1 CONTROL INFORMATION - Two cards

1(a) First Card

Columns	Note	Name	Data
5 (I)		NGR	Element group indicator. Punch 7.
6-10(I)	(1)	NELS	Number of elements in group.
11-15(I)		MFST	Element number of first element in group. Default = 1.
41-80(A)		GRHED	Optional group heading.

1(b) Second Card

Columns	Note	Name	Data
1- 5(I)		NMAT	Number of different stiffness types. Default = 1.
6-10(I)		IFIX	Fixity indicator. (a) Zero or blank: NODM must be zero (see Section 3.3). (b) 1: NODM must not be zero.

5.2 STIFFNESS TYPES - NMAT cards

Columns	Note	Name	Data
1-10(F)	(2)		Gap Clearance (CL)
11-20(F)			Stiffness K1
21-30(F)			Yield force YF1
31-40(F)			Stiffness K2
41-50(F)			Yield force YF2
51-60(F)			Stiffness K3
61-70(F)			Tangential stiffness (KF)
71-80(F)			Coefficient of friction (μ)

5.3 ELEMENT DATA - NELS cards

Columns	Note	Name	Data
1- 5(I)	(3)	MEL	Element number.
6-10(I)	(4)	NODN	Node number N.
11-15(I)		NODI	Node number I.
16-20(I)		NODJ	Node number J.
21-25(I)		NODM	Node number M. Leave blank if IFIX = 0.
26-30(I)		MAT	Stiffness type. Default = 1.
31-35(I)		KTHO	Response output code. (a) Zero or blank: no output. (b) 1: output required.
36-45(F)	(5)	TOLA	Stiffness reformulation angle tolerance (radians). Default = 0.

5.4 USER'S GUIDE NOTES

NOTE (1) The elements in the group are numbered sequentially, starting with MFST (i.e. MFST, MFST+1, MFST+2,..., MFST+NELS-1).

NOTE (2) Each stiffness type requires six constants for the normal component and two constants for the tangential components. These constants are defined in Figs. 2 and 3. Stiffnesses K1 and K2 must not be zero.

NOTE (3) Cards for all elements in the group must be provided, in order of increasing element number. That is, an element generation option is not included.

NOTE (4) Nodes N, I, and J define the bearing plane (Fig. 1). The element is connected to the structure at node N, as shown. If motions of the bearing plane are to be permitted, a fourth node, M, must be specified (fixity indicator, IFIX = 1).

Node M may then be part of a deformable structure. Nodes N and M must have identical coordinates. If the bearing plane is fixed in space (IFIX = 0), node M must be zero.

NOTE (5) Refer to Section 3.3 for a description of the stiffness reformulation angle tolerance.

REFERENCES

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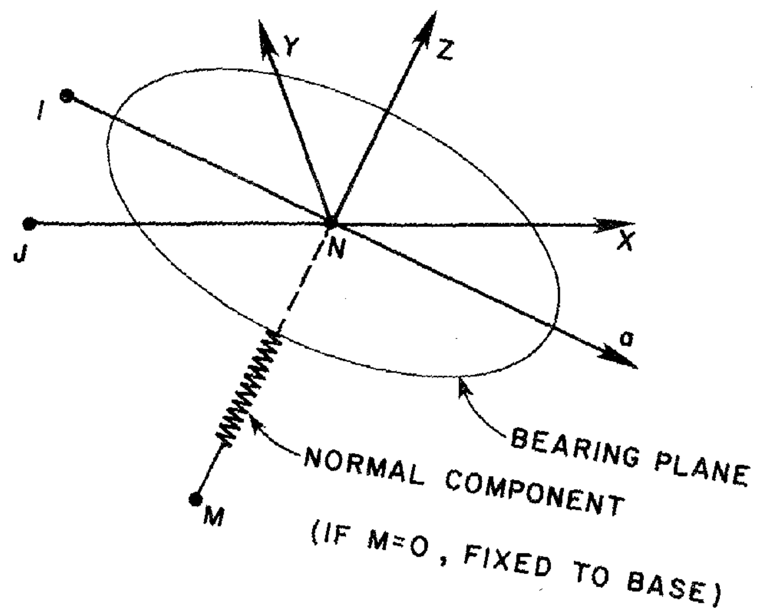

FIG. 1 ORIENTATION OF GAP-FRICTION ELEMENT

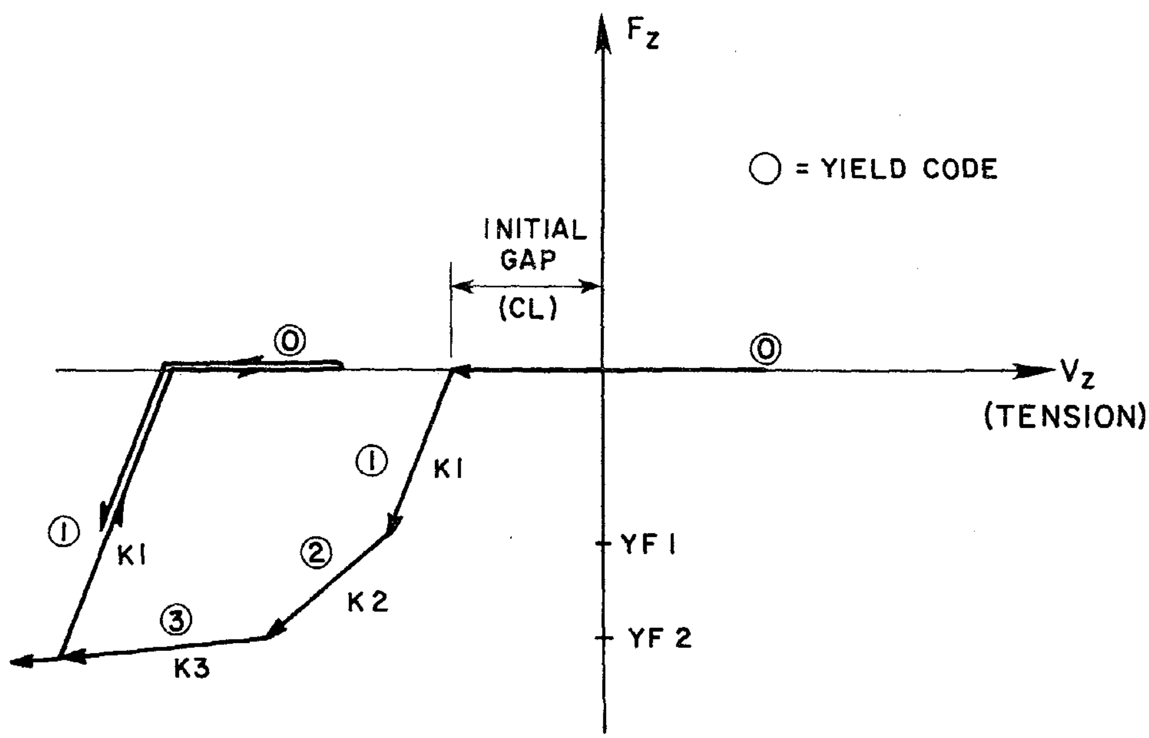

FIG. 2 FORCE-DEFORMATION BEHAVIOR OF NORMAL COMPONENT

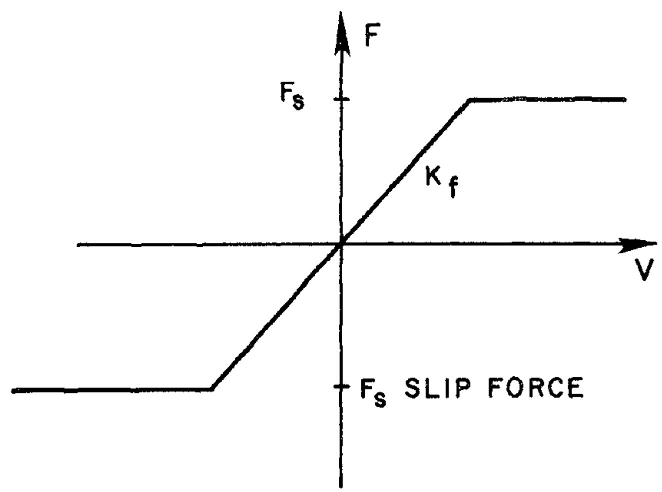

FIG. 3 FORCE-DEFORMATION BEAHVIOR OF TANGENTIAL COMPONENT

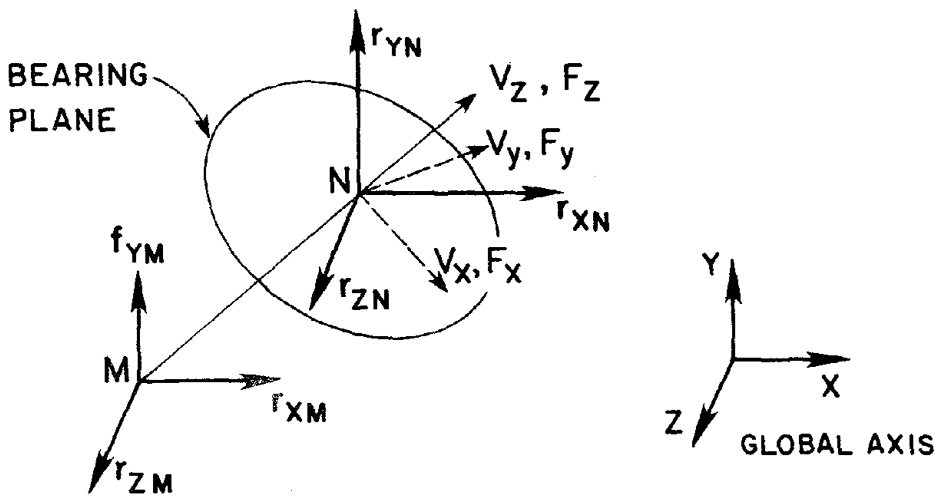

FIG. 4 DEFORMATIONS AND DISPLACEMENTS

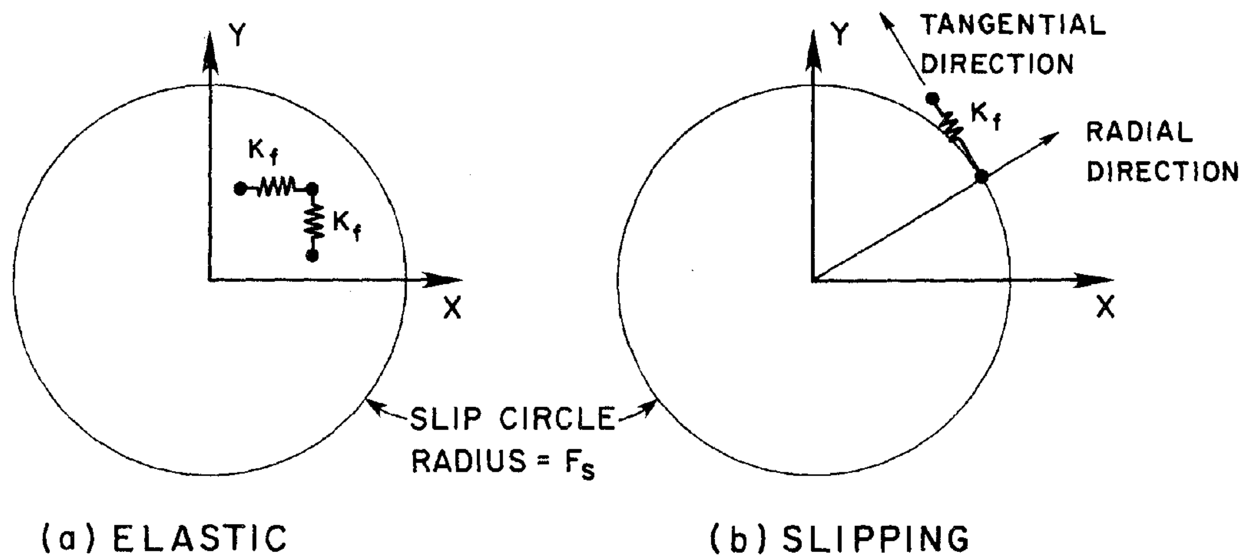

FIG. 5 STIFFNESS OF TANGENTIAL COMPONENT

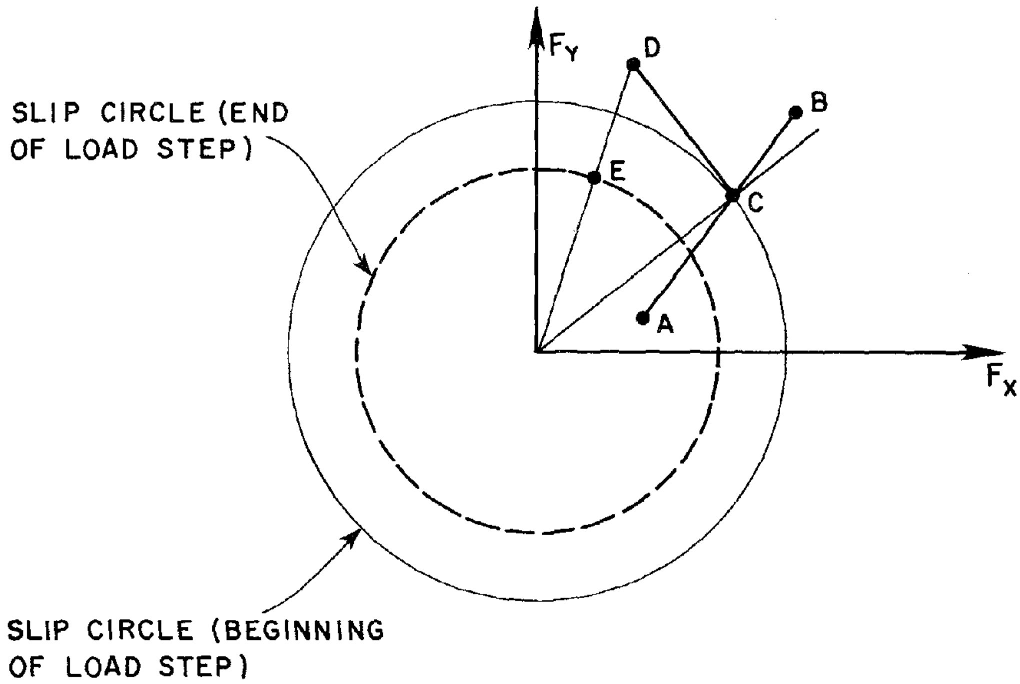

FIG. 6 STATE DETERMINATION EXAMPLE

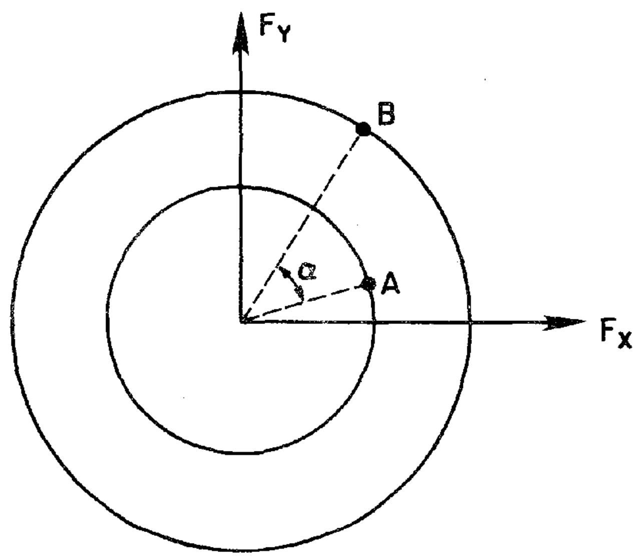

FIG. 7 STIFFNESS REFORMULATION ANGLE

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