BIAXIAL BENDING ANALYSIS OF HYDRAULIC CYLINDERS

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Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
DOCTOR OF PHILOSOPHY
May, 1979

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ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to the following individuals who made this study possible:

Dr. William P. Dawkins, major adviser and chairman of the committee, for his excellent instruction, invaluable guidance and understanding throughout this study.

Dr. John P. Lloyd, Dr. Allen E. Kelly, Dr. John W. Harvey, and Dr. Donald E. Boyd for their helpful assistance and advisement while serving on the author's advisory committee.

Dr. K. L. Seshasai, for his friendship, encouragement and counsel.

Dr. S. K. R. Iyengar, for his help and friendship during the study.

Fellow graduate students, notably Dr. S. S. Bandy, T. S. Kale, R. Viswanathan, and S. K. Hari for their friendship and assistance.

Ms. Charlene Fries, for her excellent and meticulous typing of the manuscript.

The author is greatly indebted to his parents for their sacrifices, encouragement, and guidance.

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LIST OF SYMBOLS

$\{C\}$	crookedness angle matrix
d_{ro}	outer diameter of the rod
d_{ri}	inner diameter of the rod
d_{ci}	inner diameter of the cylinder
E	modulus of elasticity
e_{cy}	eccentricity at cylinder end along Y axis
e_{cz}	eccentricity at cylinder end along Z axis
e_{ry}	eccentricity at rod end along Y axis
e_{rz}	eccentricity at rod end along Z axis
$\{F\}^i$	nodal force matrix
F_i^p	lateral force on ith piston ring
F_i^r	lateral force on ith rod bearing
F_b^p, F_j^p	lateral force at the piston head back and front side metal-to-metal contact points, respectively
F_b^r, F_j^r	lateral force at the stuffing box inside and outside metal-to-metal contact points, respectively
I	moment of inertia of the element
$[K]^i$	stiffness matrix of element i
K_{ii}^a K_{ij}^a K_{ji}^a K_{jj}^a	partitioned submatrices of the element a
L	length of the element
M_{ry}	moment at the rod end about Y axis
M_{rz}	moment at the rod end about Z axis
M_{cy}	moment at the cylinder end about Y axis
M_{cz}	moment at the cylinder end about Z axis

$(M_y)_j^i$	moment about Y axis at the jth node of the ith element
$(M_z)_j^i$	moment about Z axis at the jth node of the ith element
M	number of piston bearings and seals in the piston head
M_G	bending moment at the sliding connection
N	number of rod bearings and seals in the stuffing box
P	axial load acting on an element
p	fluid pressure
PCL	radial distance between piston head and stuffing box
r	radial distance from the centroidal axis
RCL	radial clearance between the rod and stuffing box
$(V_y)_j^i$	shear force along Y axis at the jth node of the ith element
$(V_z)_j^i$	shear force along Z axis at the jth node of the ith element
$(v)_j^i$	translation along Y axis at the jth node of the ith element
$(w)_j^i$	translation along Z axis at the jth node of the ith element
w_c	weight of cylinder/unit length
w_{ph}	weight of piston head/unit length
w_{rod}	weight of rod/unit length
w_{sb}	weight of stuffing box/unit length
X, Y, Z	direction of the coordinate axes
δ_b^p	displacement of piston head back edge
δ_b^r	displacement of stuffing box inside edge
δ_j^p	displacement of piston head front side
δ_j^r	displacement of stuffing box outside edge

θ_c crookedness angle in the bending plane

ρ_j^i rotation about Y axis at the jth node of the ith element

ρ_c component of crookedness angle along Z axis

β_j^i rotation about Z axis at the jth node of the ith element

β_c component of the crookedness angle along Y axis

ϕ angle to indicate the position of the eccentric load

CHAPTER I

INTRODUCTION

Hydraulic cylinders are the most common actuators in fluid power systems. In addition to working as fluid power components, they are required to function as structural members as well and consequently need to be designed to meet specified structural requirements. The successful performance of the hydraulic cylinder as a load carrying unit is governed by the necessity that the stresses and deflections produced at any particular load be less than tolerable limits. Because axial compression is the most prominent load system acting on the hydraulic cylinder, the possibility of lateral buckling must also be examined.

Until recently, certain empirical formulas and numerous simplifying assumptions were used in hydraulic cylinder design. The assumptions range from considering the hydraulic cylinder to be a slender circular column with a radius equal to that of the rod region to assuming the cylinder to be a stepped column. The buckling loads for these simple systems were the basis for design. Of late, however, the flexibility at the interface of the cylinder and the rod due to the presence of the seals and bearings and the corresponding reduction in the load carrying capacity have been considered (10). The above analyses were restricted to axial loads having eccentricity in the plane of the cylinder self-weight.

1.1 Objectives of the Study

The primary objective of this work was to extend the method of analysis developed by Seshasai (10) for planar analysis to permit analysis of fluid power cylinders subjected to biaxial bending and to include effects of arbitrary support locations and eccentricities. The steps taken to achieve this objective were:

1. Review previous methods of analysis.

2. Develop a finite element model of the cylinder subjected to biaxial bending and to include such effects as the crookedness angle at the cylinder/rod interface, arbitrary location and eccentricity of supports, arbitrary location and eccentricity of external loads, and influence of pressurized hollow rods.

3. Develop a computer program to apply the method of analysis.

4. Verify the method of analysis by comparing the results with previous analytical and experimental investigations.

5. Illustrate the application of the method to cylinders for which no previous analysis was available.

CHAPTER II

LITERATURE REVIEW

Early investigation (1) of hydraulic cylinders was based on the assumptions that the cylinder would always fail by buckling of the rod and that the cylinder portion is infinitely stiff. These assumptions were based on the misconception that the cylinder portion would behave as a pressurized pipe closed at both ends; hence the internal pressure would produce a stabilizing axial tensile force in the cylinder and prevent it from buckling.

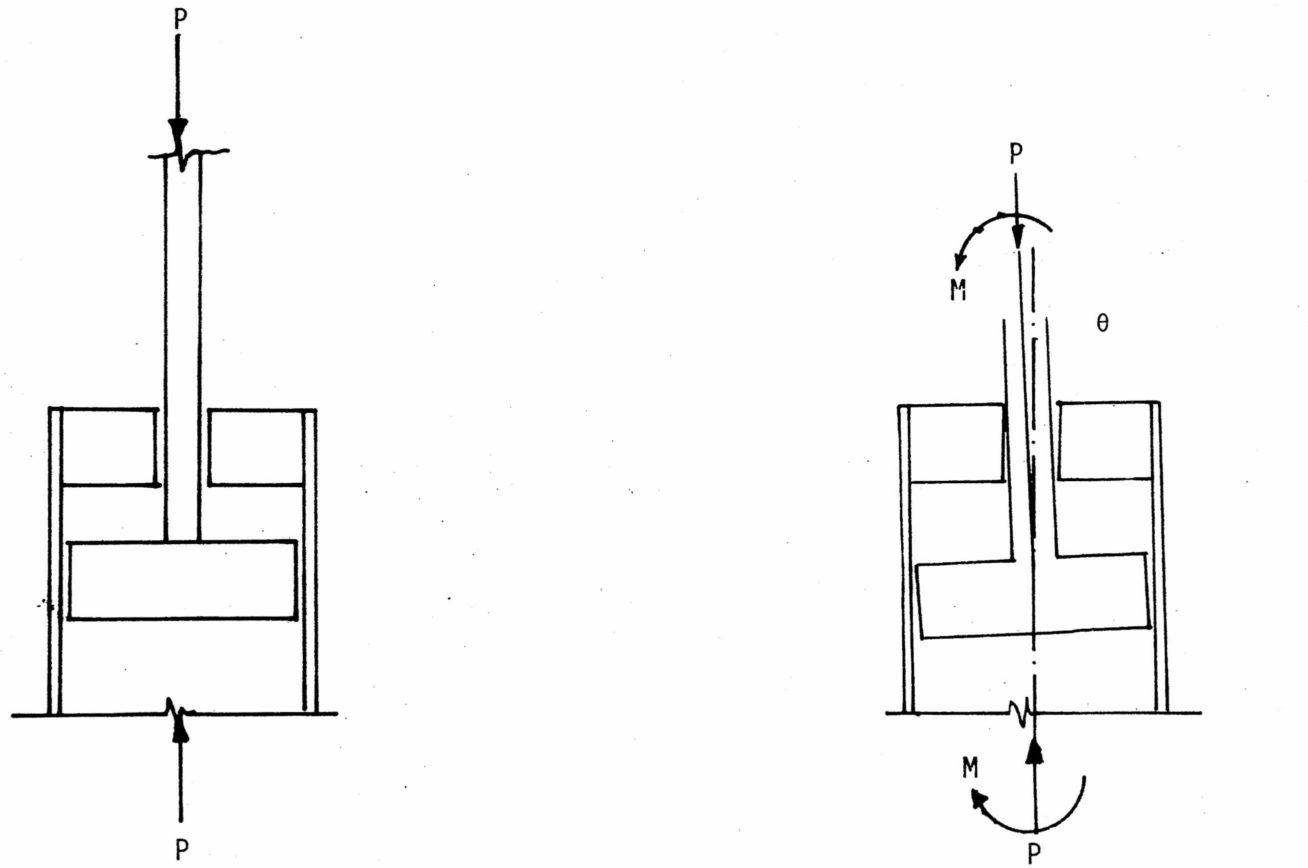
However, in hydraulic cylinders the load is transferred to the fluid directly through the sliding connection and no axial force is present in the walls of the cylinder. Under the effect of the internal fluid pressure the cylinder acts as a fluid-filled column and is susceptible to buckling (2) (3). The formulation of a differential equation governing the elastic response of stepped columns was formulated by investigators (4) (5) (6) (7).

The hydraulic cylinder can be considered as a stepped column only for buckling analysis. The stepped column analysis cannot be used to determine stress failure of the cylinder, since the stress distribution in the stepped column and hydraulic cylinder differ in the cylinder portion. Because of the internal fluid pressure, the cylinder portion is subjected to hoop stresses which are absent in stepped columns. For buckling analysis, the internal pressure in the cylinder can be replaced by an axial load on the walls of the cylinder equal to pressure times the cross-sectional area of the bore, and the bending moment distribution for the stepped column will be the same as for the pressurized cylinder.

The presence of compressible seals and bearings at the interface renders the hydraulic cylinder more flexible than the stepped column. Under the effect of the axial load, the cylinder deflects and lateral forces perpendicular to the axis of the cylinder act on the bearings and seals. These forces transfer moments across the interface and develop a crookedness angle between the cylinder and the rod (Figure 1). The crookedness angle interacts with the axial load to increase the deflections, moments, and stresses (8) and hence reduces the load carrying capacity of the cylinder.

Several investigators have attempted to account for the crookedness angle effect by: introducing a small eccentricity in the axial load (1); assuming a constant crookedness angle (9); or calculating the crookedness angle from an empirical formula (3). In a more rigorous and complete analysis (8), the bearings and seals were modeled as linear springs and a moment-crookedness angle relationship was developed. An iterative procedure was used to account for the crookedness angle effect.

Although the more complete procedure (10) for dealing with the crookedness angle effect permits consideration of a wide variety of loading and support conditions, it is restricted to loading and support eccentricities only in the plane of the cylinder self-weight.



(a) Straight Cylinder, Zero Crookedness Angle

(b) Deflected Cylinder, Development of Crookedness Angle θ

Figure 1. Crookedness Angle

CHAPTER III

METHOD OF ANALYSIS

In order to define a method sufficiently general to handle a wide variety of parameters, it is necessary to represent the hydraulic cylinder by a model which has geometric and response characteristics as close to the original structure as possible.

In the present study the model is composed of space frame elements, each having eight degrees of freedom. The physical properties of these elements correspond to the particular region of the hydraulic cylinder they represent. The crookedness angle is taken into account by introducing a fictitious rotary spring at the junction of the rod and the cylinder.

In conventional finite element analysis, the displacement characteristics are assumed and the accuracy of the solution improves with a reduction in element size. However, in the present study, because the force-displacement characteristics are derived from the differential equations governing the bending of beams subjected to axial and lateral loads, the minimum number of elements necessary to represent the geometry of the hydraulic cylinder gives an accurate solution.

3.1 Assumptions

The assumptions used in the development of the analysis are as follows.

1. All materials are linearly elastic, isotropic, and homogeneous.

2. Deflections are small compared to the length of the cylinder.

3. The axes of the cylinder and the rod are co-linear before loading.

4. The rod is fully extended but the piston is not in contact with the stuffing box.

5. The length of the stuffing box is small compared to the length of the cylinder.

6. The rod and cylinder portions comprising the interface remain straight.

7. The bearings and seals at the sliding connection can be replaced by piecewise linear springs.

8. There is no axial force transfer through friction in either the piston head or the stuffing box bearings.

9. Cylinder supports can be anywhere along the length of the cylinder. However, the sliding connection must be between the cylinder and the rod supports.

10. The system is not subjected to torsion.

3.2 Factors Affecting the Failure

Failure of a hydraulic cylinder is assumed to occur when the stress at any point along the hydraulic cylinder exceeds a prescribed limit. The following factors affect the load carrying capacity of the hydraulic cylinder.

In hydraulic cylinders axial compression is the most predominant load system. In the cylinder portion it results in hoop stresses due to the fluid pressure, and in the rod portion it produces compressive stresses (and hoop stresses in pressurized rods). Due to the interaction of the axial load with deflections, longitudinal bending stresses are produced both in the rod and in the cylinder.

The crookedness angle reduces the stiffness at the interface and increases the deflections, moments, and stresses, and hence reduces the load carrying capacity of the cylinder.

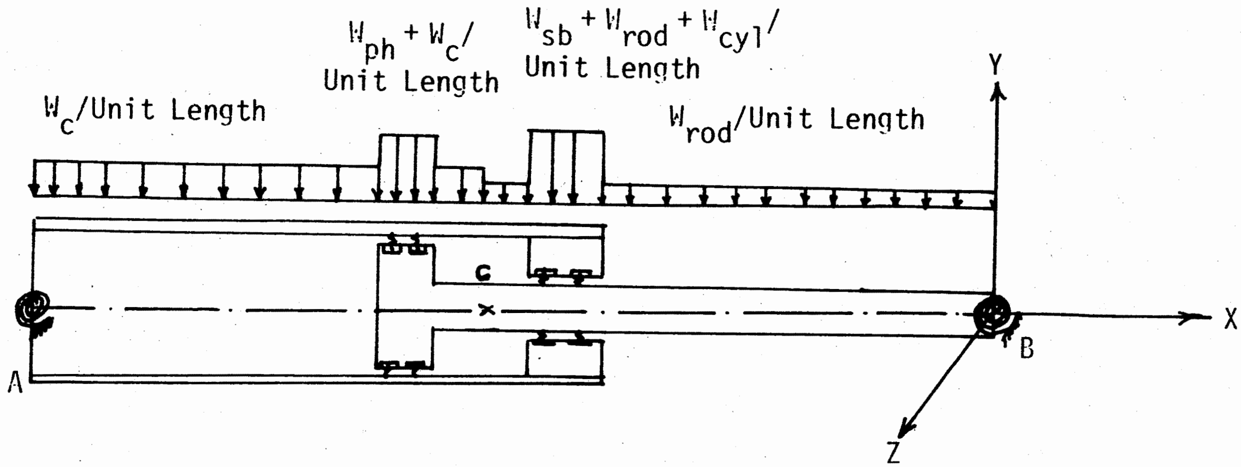
Stop-tubes are provided in hydraulic cylinders to increase the lever arm of the moment carried by the sliding connection and to reduce the contact forces. A stop-tube reduces the crookedness angle and increases the load carrying capacity.

Eccentricities of applied loads or supports and the effect of self-weight cause additional bending moments and stresses.

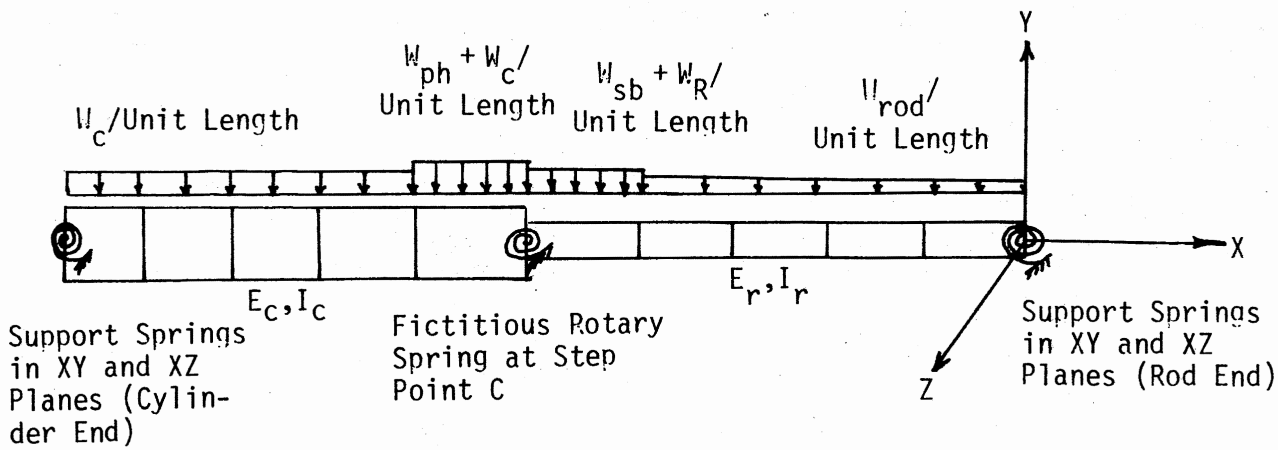
The cylinder support type, location, and the number of supports determine the effective length of the hydraulic cylinder and, hence, the load carrying capacity. Friction moments in the pin supports also affect the bending moment at any section along the length of the cylinder. Friction moments may have either a stabilizing or a destabilizing effect on the cylinder, depending upon the direction of rotation of the pins.

3.3 Analytical Model

The assumptions discussed above permit the hydraulic cylinder to be modeled as shown in Figure 2(a). Point C is the location at which the cylinder and the rod axis intersect when the cylinder is in a deflected position. The portion of the system to the left of C is considered to possess the characteristics of the cylinder portion and that to the right is treated as a part of the rod. The self-weight is assumed to act in



(a) Hydraulic Cylinder



(b) Finite Element Model

Figure 2. Analytical Model

the negative Y direction. The bearings and seals in the gland region are modeled as linear springs as described in Reference (10).

The supports at the end of the cylinder can either be pinned (permit free rotation about the Y or Z axes) or fixed. For illustrative purposes only two supports have been shown in Figure 2(a). However, any number of supports can be included in the analysis.

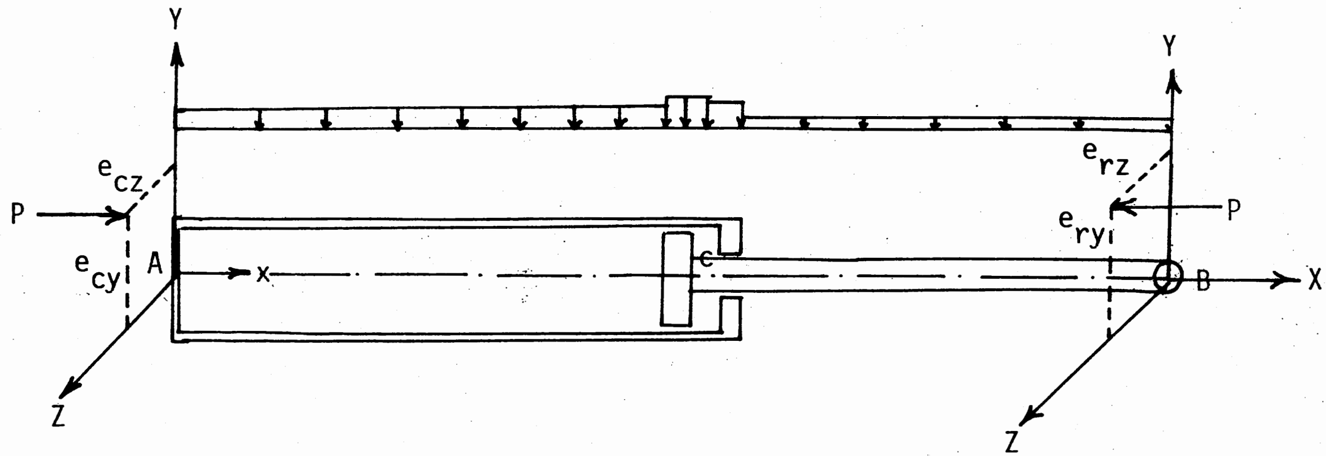
The finite element model shown in Figure 2(b) represents the cylinder shown in Figure 2(a). The cylinder and the rod are treated as one-dimensional space frame elements. The effect of the crookedness angle is taken into account by introducing a rotary spring at point C.

3.4 Method of Analysis

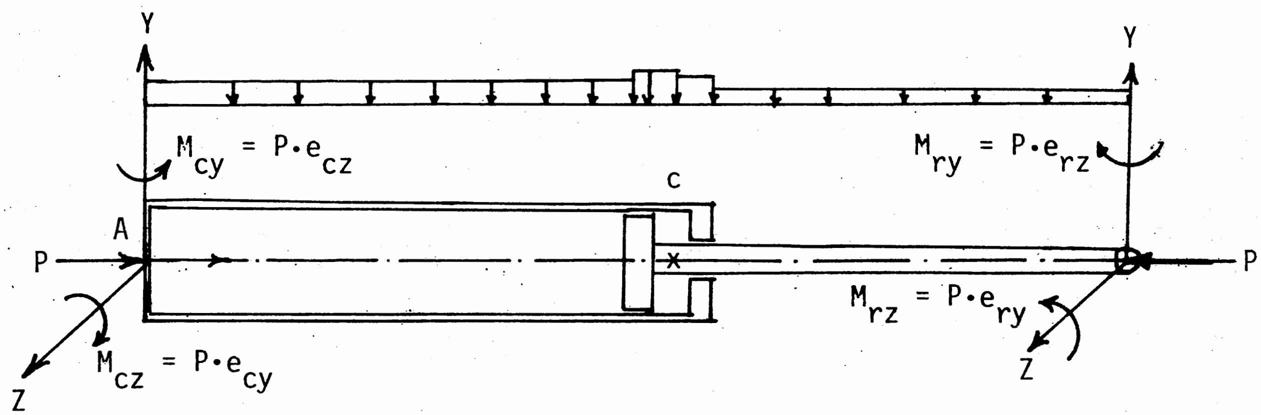
The present study includes the analysis of hydraulic cylinders subjected to axial loads acting at arbitrary eccentricities, as shown in Figure 3(a). For the purposes of analysis the eccentric load is replaced by an equivalent system of axial load P and moments M_{ry}, M_{rz}, M_{cy}, and M_{cz}, as shown in Figure 3(b).

As discussed earlier, the model of the hydraulic cylinder is a stepped beam-column composed of space frame elements with a flexible joint at the sliding connection. Each node of the model has four degrees of freedom, restraint conditions, and forces. The sliding connection of the hydraulic cylinder is modeled as a combination of a cylinder element and a rod element separated by a fictitious rotary spring.

To begin the solution procedure, an initial value of the crookedness angle is estimated. In the case of nonvertical cylinders the initial crookedness angle is due to the self-weight moments, and in vertical cylinders an initial value is assumed. The crookedness angle so determined



(a) Original System of Forces



(b) Equivalent System of Forces

Figure 3. Equivalent Force System

may be in an arbitrary bending plane and is resolved into components about the Y and Z axes. The crookedness angle produces additional forces at the gland and, hence, additional deflection. Consequently, due to the interaction of the axial load with the deflection, the moment distribution along the hydraulic cylinder length and the moment acting at the gland are changed. The moments at the gland so calculated will be about reference axes Y and Z. These moments are added vectorially to determine the interface moment in the bending plane and a new estimate of the resultant crookedness angle is calculated. The process is continued until values of the crookedness angle, obtained from successive iterations, agree to a prescribed tolerance.

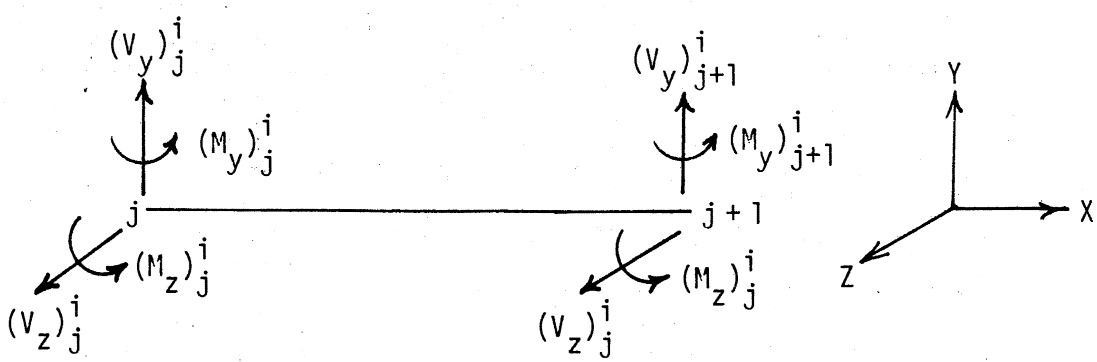
After a constant value of the crookedness angle is obtained from successive iterations, the maximum stresses and deflections in the cylinder and the rod are calculated and compared with prescribed limiting values. If the calculated stresses are below the limiting values, the axial load is incremented until limiting conditions are reached.

Thus the process involves a dual iterative approach to calculate a constant value of crookedness angle for a particular axial load and to find the value of the axial load at which the stresses and deflections are very close to the tolerable limits.

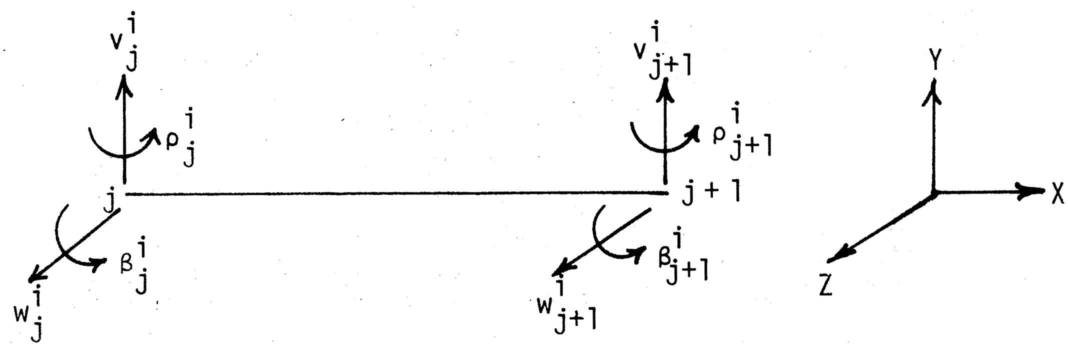
3.5 Element Stiffness Matrix

The model of the cylinder is an assemblage of space frame elements and conventional matrix analysis techniques are applied to determine the displacements and forces in the model.

Figure 4(a) shows the forces acting on a single element of the structure. V_y and V_z are shear forces in the Y and Z directions. M_y



(a) Member End Forces



(b) Member End Displacements

Figure 4. Forces and Displacements in a Beam Element

and M_z are moments about the Y and Z axes, respectively. Figure 4(b) shows the displacements v and w in the Y, Z directions, along with the rotations ρ and β about the Y and Z axes, respectively. The subscripts in the figure correspond to the node numbers and the superscripts correspond to the element numbers. The force-displacement relation for an element is given by

$$\{F\}^i = [K]^i \{u\}^i + \{FEM\}^i \tag{3.1}$$

where

{F} = nodal force matrix;

{u} = nodal displacement matrix;

{K} = stiffness matrix; and

{FEM} = fixed end moments.

and

$$\{F\}^i = \begin{bmatrix} (V_y)^i_j \\ (M_y)^i_j \\ (V_z)^i_j \\ (M_z)^i_j \\ \hdashline (V_y)^i_{j+1} \\ (M_y)^i_{j+1} \\ (V_z)^i_{j+1} \\ (M_z)^i_{j+1} \end{bmatrix} \tag{3.2a}$$

$$u^{i} = \begin{bmatrix} v_j^i \\ \rho_j^i \\ w_j^i \\ \beta_j^i \\ \hline v_{j+1}^i \\ \rho_{j+1}^i \\ w_{j+1}^i \\ \beta_{j+1}^i \end{bmatrix} \tag{3.2b}$$

The derivation of the stiffness matrix for the frame element taking the axial load into consideration is shown in Appendix A. Equation (3.1) is expressed in matrix form as shown in Figure 5 (Equation (3.4)), where

E = modulus of elasticity of element i;

L = length of the element;

I = moment of inertia of the element;

q = self-weight/unit length; and

P = axial load on the member.

The stiffness coefficients are in terms of R, S, T, and C, where

$$R = \frac{4EI}{L^2}\,[K(1+C)]$$

$$T = \frac{4EI}{L^3}\,[2K(1+C) - \frac{\phi^2}{4}] \tag{3.3}$$

$$S = K(\frac{4EI}{L})$$

which are in terms of

$$
\begin{bmatrix} (V_y)_j^i \\ (M_y)_j^i \\ (V_z)_j^i \\ (M_z)_j^i \\ (V_y)_{j+1}^i \\ (M_y)_{j+1}^i \\ (V_z)_{j+1}^i \\ (M_z)_{j+1}^i \end{bmatrix}
=
\begin{bmatrix}
T & 0 & 0 & R & -T & 0 & 0 & R \\
0 & S & -R & 0 & 0 & CS & R & 0 \\
0 & -R & T & 0 & 0 & -R & -T & 0 \\
R & 0 & 0 & S & -R & 0 & 0 & CS \\
-T & 0 & 0 & -R & T & 0 & 0 & -R \\
0 & CS & -R & 0 & 0 & S & R & 0 \\
0 & R & -T & 0 & 0 & R & T & 0 \\
R & 0 & 0 & CS & -R & 0 & 0 & S
\end{bmatrix}
\begin{bmatrix} v_j^i \\ p_j^i \\ w_j^i \\ \beta_j^i \\ v_{j+1}^i \\ p_{j+1}^i \\ w_{j+1}^i \\ \beta_{j+1}^i \end{bmatrix}
+
\begin{bmatrix}
\frac{q\ell}{2} \\
0 \\
0 \\
\frac{q\ell^2}{2} - \frac{q\ell^2}{2\Delta_c}(2\text{Sin}\phi - \phi\text{Cos}\phi - \phi) \\
\frac{q\ell}{2} \\
0 \\
0 \\
\frac{q\ell^2}{2\phi}\text{Sin}\phi - \frac{q\ell^2}{\phi^2} + \frac{q\ell^2}{2\Delta_c}(2\text{Sin}\phi - \phi\text{Cos}\phi - \phi)\text{Cos}\phi
\end{bmatrix}
\qquad (3.4)
$$

Figure 5. Stiffness Relationship for the Single Element

$$\phi^2 = \frac{PL^2}{EI}$$

$$K = \frac{3\lambda^2}{4\lambda^2 - \alpha^2}$$

$$C = \frac{\alpha}{2\lambda}$$

$$\lambda = \frac{3(1 - \phi\cot\phi)}{\phi^2}$$

$$\alpha = \frac{-6(1 - \phi\operatorname{cosec}\phi)}{\phi^2}$$

$$\Delta_c = \phi(2 - 2\cos\phi - \phi\sin\phi)$$

3.6 Constraint Equations at the Gland

A simple finite element model of the hydraulic cylinder is shown in Figure 6. Elements 1 and 4 represent the cylinder and the rod, respectively, and elements 2 and 3 together constitute the gland. The point C (joint 3) corresponds to the location at which the cylinder and the rod axes intersect. Elements 2 and 3 are assumed to be parts of the cylinder and the rod, respectively, and have corresponding stiffness properties.

The purpose of developing the constraint equation is to incorporate the effect of the crookedness angle at the gland. The forces acting at the gland are shown in Figure 7. Displacements v, ρ, w, β correspond to forces V_y, M_y, V_z, and M_z, respectively. Superscripts on the forces and displacements in Figures 6 and 7 correspond to element numbers and subscripts correspond to node numbers.

At C, due to the crookedness angle there is a discontinuity of rotation between the cylinder and the rod. In other words, at C the relationships between the displacement of nodes 2 and 3 are

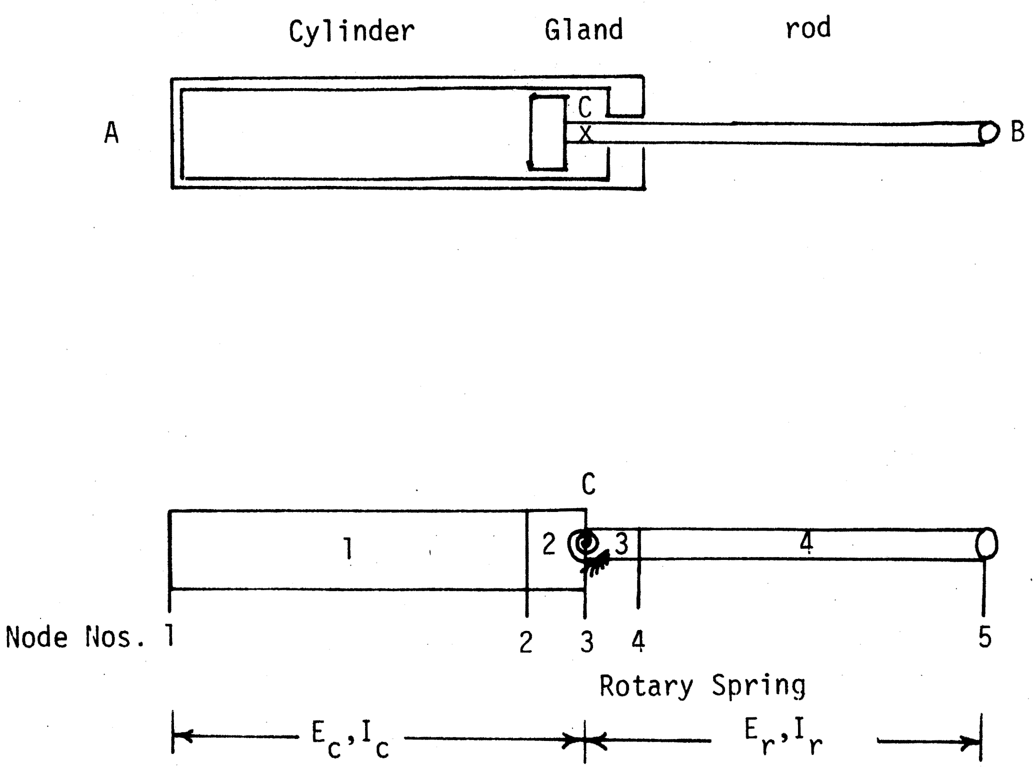
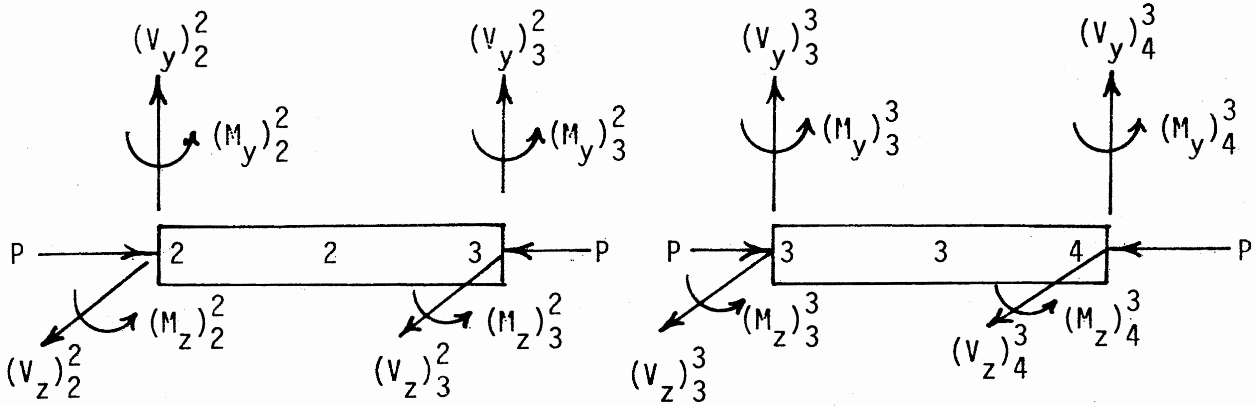
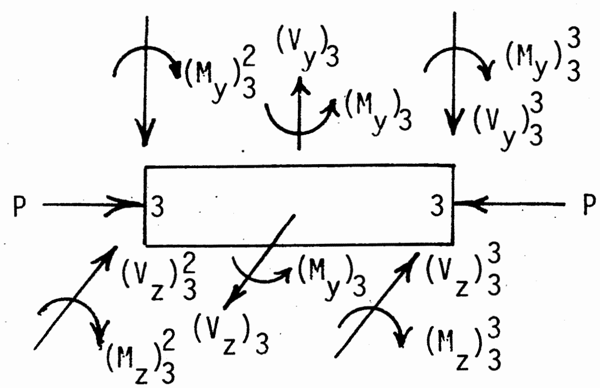


Figure 6. Finite Element Model of the Hydraulic Cylinder



(a) Free Body Diagram of Element No. 2

(b) Free Body Diagram of Element No. 3



(c) Free Body Diagram of Joint 3

Figure 7. Forces Acting at the Gland

$$
\begin{aligned}
\rho_3^2 &= \rho_3^3 - \rho_c \\
\beta_3^2 &= \beta_3^3 - \beta_c \\
v_3^2 &= v_3^3 \\
w_3^2 &= w_3^3
\end{aligned}
\tag{3.5}
$$

where ρ_c and β_c are components of the crookedness angle about the Y and Z axes, respectively.

From Figure 7, equilibrium of joint 3 can be expressed as

$$
\begin{aligned}
(V_y)_3^2 + (V_y)_3^3 &= (V_y)_3 \\
(M_y)_3^2 + (M_y)_3^3 &= (M_y)_3 \\
(V_z)_3^2 + (V_z)_3^3 &= (V_z)_3 \\
(M_z)_3^2 + (M_z)_3^3 &= (M_z)_3
\end{aligned}
\tag{3.6}
$$

The stiffness matrix for an element a can be partitioned as

$$
[K]^a = \begin{bmatrix} K_{ii}^a & K_{ij}^a \\ K_{ji}^a & K_{jj}^a \end{bmatrix}
$$

where i and j are the left and right node numbers of element a. For elements 2 and 3, the force-displacement relationship can be expressed as

$$
\begin{bmatrix} K_{22}^2 & K_{23}^2 \\ K_{32}^2 & K_{33}^2 \end{bmatrix} \begin{bmatrix} U_2^2 \\ U_3^2 \end{bmatrix} = \begin{bmatrix} F_2^2 \\ F_3^2 \end{bmatrix}
\tag{3.7}
$$

$$\begin{bmatrix} K_{33}^3 & K_{34}^3 \\ K_{43}^3 & K_{44}^3 \end{bmatrix} \begin{bmatrix} U_3^3 \\ U_4^3 \end{bmatrix} = \begin{bmatrix} F_3^3 \\ F_4^3 \end{bmatrix} \tag{3.8}$$

where {U} and {F} are the displacements and the forces, respectively, at the nodes. A combination of Equations (3.6), (3.7), and (3.8) results in

$$K_{32}^2 U_2^2 + K_{33}^2 U_3^2 + K_{33}^3 U_3^3 + K_{34}^3 U_4^3 = F_3 \tag{3.9}$$

$$K_{43}^3 U_3^3 + K_{44}^3 U_4^3 = F_4 \tag{3.10}$$

Application of the slope compatibility relations (Equation (3.5)) allows the joint equilibrium conditions (Equations (3.9) and (3.10)) to be expressed as

$$[K_{32}^2] \begin{bmatrix} v_2^2 \\ \rho_2^2 \\ w_2^2 \\ \beta_2^2 \end{bmatrix} + [K_{32}^2 + K_{33}^3] \begin{bmatrix} v_3^2 \\ \rho_3^2 \\ w_3^2 \\ \beta_3^2 \end{bmatrix} + [K_{34}^3] \begin{bmatrix} v_4^3 \\ \rho_4^3 \\ w_4^3 \\ \beta_4^3 \end{bmatrix} = \begin{bmatrix} (V_y)_3 \\ (M_y)_3 \\ (V_z)_3 \\ (M_z)_3 \end{bmatrix} - [K_{33}^3] \begin{bmatrix} 0 \\ \rho_c \\ 0 \\ \beta_c \end{bmatrix} \tag{3.11}$$

$$[K_{43}^3] \begin{bmatrix} v_3^2 \\ \rho_3^2 \\ w_3^2 \\ \beta_3^2 \end{bmatrix} + [K_{44}^3] \begin{bmatrix} v_4^3 \\ \rho_4^3 \\ w_4^3 \\ \beta_4^3 \end{bmatrix} = \begin{bmatrix} (V_y)_4 \\ (M_y)_4 \\ (V_z)_4 \\ (M_z)_4 \end{bmatrix} - [K_{43}^3] \begin{bmatrix} 0 \\ \rho_c \\ 0 \\ \beta_c \end{bmatrix} \tag{3.12}$$

All displacements at joint 3 are expressed in terms of the displacement of element 2, i.e., $\{U\}_3^2$.

Denoting the crookedness angle matrix as {C}, the constraint equations at the gland, Equations (3.11) and (3.12) can be expressed as

$$[K_{32}^2]\{U_2\} + [K_{32}^2 + K_{33}^3]\{U_3\} + [K_{34}^3]\{U_4\} = \{F\}_3 - [K_{33}^2]\{C\} \tag{3.13}$$

$$[K_{43}^3]\{U_3\} + [K_{44}^3]\{U_4\} = \{F\}_4 - [K_{43}^3]\{C\} \tag{3.14}$$

where the displacements $\{U\}_1$, $\{U\}_2$, and $\{U\}_3$ are the nodal displacements. The overall force-deformation relationship for the entire model is shown in Figure 8 (Equation (3.15)).

3.7 Determination of the Crookedness Angle

As discussed earlier, the crookedness angle reduces the load carrying capacity of the hydraulic cylinder and, hence, it is necessary to understand the moment-crookedness angle relationship at the sliding connection. In the present study the crookedness angle relationship is based on the method followed by Seshasai (10).

The crookedness angle is a function of the material properties of the bearings and seals and the geometry of the interface. As the cylinder deflects, the moment at the gland as well as the lateral forces acting on the bearings and seals increase. Because of the lateral forces, the seals and bearings are compressed and a crookedness angle develops at the sliding connection.

With an increase in the gland moment, a contact point may occur either at the front edge of the piston head or at the outside edge of the stuffing box, at which time the relationship between the moment and the

$$\begin{bmatrix} K_{11}^1 & K_{12}^2 & & & \\ K_{21}^1 & K_{22}^1 + K_{22}^2 & K_{23}^2 & & \\ & K_{32}^2 & K_{33}^2 + K_{33}^3 & K_{34}^3 & \\ & & K_{43}^3 & K_{44}^3 + K_{44}^4 & K_{45}^4 \\ & & & K_{54}^4 & K_{55}^4 \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 - [K_{33}]^2\{C\} \\ F_4 - [K_{43}]^3\{C\} \\ F_5 \end{bmatrix} \tag{3.15}$$

Figure 8. Stiffness Relation for the Complete Model

crookedness angle changes. The contact point introduces a kinematic constraint and a lateral force is developed at the point of contact. The occurrence of the contact point is dependent upon clearances between the piston head and the cylinder wall, and between the stuffing box and the rod as well as the lengths of the piston head, the stuffing box, and the sliding connection.

With an increase in the load, the moment at the gland increases and a second contact point may occur. The crookedness angle becomes constant after the occurrence of two contact points. Depending upon the configuration of the sliding connection, pairs of contact points may occur in three different combinations, such as the outside and inside edges of the stuffing box, the front edge of the piston head and the stuffing box, or the front and back edges of the piston. The relationship between the moment and the crookedness as derived in Reference (10) is given in Appendix B.

3.8 Stress Calculation

Failure in hydraulic cylinders can occur due to excessive axial stress, excessive hoop stresses, a combination of axial, bending, and hoop stresses resulting in excessive shear stresses, or excessive lateral deflections.

The critical load of a hydraulic cylinder is reached when the stress at any point reaches a prescribed limit. The stresses to be compared with the limit values are:

1. Maximum hoop stress in the cylinder (and in the rod for pressurized rods).

2. The shear stress at the point of maximum bending moment.

3. The longitudinal stress due to the combination of the axial load and bending moments at the extreme fibers at the point of maximum bending moment.

The methods for calculating the stresses are described in the following sections.

3.8.1 Axial Stresses

Axial stresses in a hydraulic cylinder are due to the axial loading of the system and are parallel to the axis of the cylinder. Because of the presence of the sliding connection, axial stresses are not present in the cylinder portion of the hydraulic cylinder. The axial stress in the rod portion is compressive and is given as follows.

Solid rod:

$$\sigma_{axial} = \frac{4P}{\pi d_{ro}^2} \tag{3.16}$$

Hollow rod without fluid pressure:

$$\sigma_{axial} = \frac{4P}{\pi (d_{ro}^2 - d_{ri}^2)} \tag{3.17}$$

Hollow rod with fluid pressure:

$$\sigma_{axial} = \frac{P(d_{ci}^2 - d_{ri}^2)}{(d_{ro}^2 - d_{ri}^2)} \tag{3.18}$$

where

d_{ro} = outer diameter of the rod;

d_{ri} = inner diameter of the rod; and

d_{ci} = inner diameter of the cylinder.

3.8.2 Bending Stresses

The bending stress at any point along the length of the cylinder is given by

$$\sigma_{bending} = \frac{Mr}{I} \tag{3.19}$$

where M is the resultant bending moment at any cross section, r is the radial distance from the centroidal axis at which the bending stress is required, and I is the moment of inertia of the cross section.

3.8.3 Hoop Stresses

Hoop stresses vary from a maximum at the inner surface of the tube to a minimum at the outer surface. At the inner surface the hoop stress is

$$\sigma_{hi} = p\,\frac{d_o^2 + d_i^2}{d_o^2 - d_i^2} \tag{3.20}$$

At the outer surface the hoop stress is

$$\sigma_{ho} = \frac{2d_i^2}{d_o^2 - d_i^2} \tag{3.21}$$

where p is the fluid pressure.

3.8.4 Shear Stresses

The longitudinal stresses (bending and axial stresses) and the hoop stress act in mutually perpendicular directions and are principal stresses. Hence the maximum shear stress at any point is given by

$$\sigma_{shear} = \frac{\sigma_{hoop} + \sigma_{axial} + \sigma_{bending}}{2} \tag{3.22}$$

with appropriate signs.

CHAPTER IV

COMPUTER PROGRAM

The method of analysis described in the preceding chapters has been programmed in the FORTRAN language for solution on the IBM 370 computer. Only minor changes may be necessary to execute the program on other types of computers having the FORTRAN compiler.

The program listed in Appendix D permits a maximum of only seven elements in the finite element model. However, the dimensions in the driver routine may be increased to permit analysis of a model with any number of elements, limited only by the size of the computing system. Detailed input information is also presented in Appendix D.

The program, named SACFI, has the following options.

1. Determination of the critical load and analysis for a certain factored load. The factor of safety may be either applied to the stress or to the load.

2. Analysis for a particular fluid pressure.

3. Analysis to determine the required length of a stop-tube.

The computer program has a driver routine and 18 subroutines. Double precision arithmetic is used in the program execution. A summary flow diagram is presented in Figure 9.

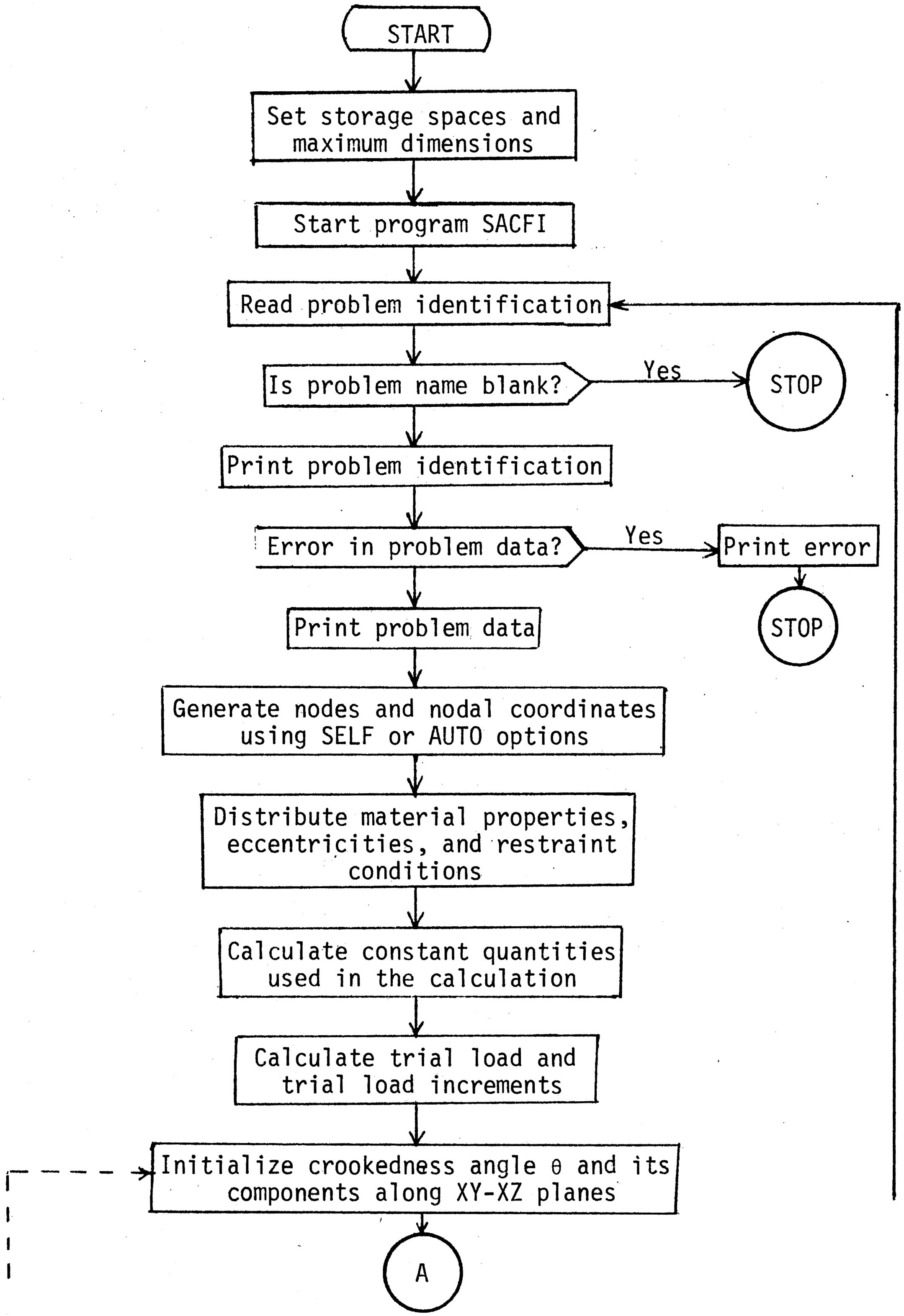


Figure 9. Flow Chart for Program SACFI

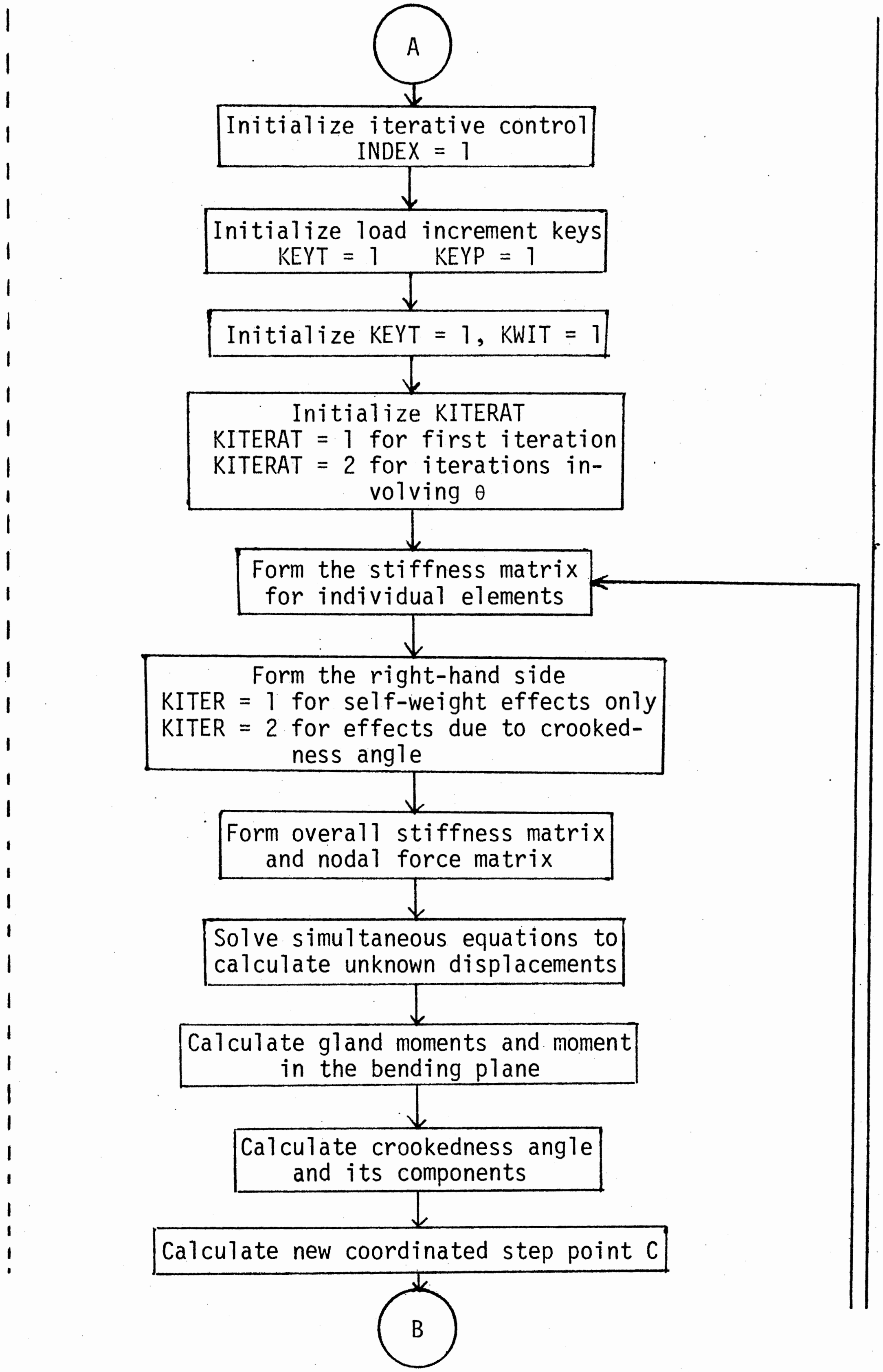


Figure 9. (Continued)

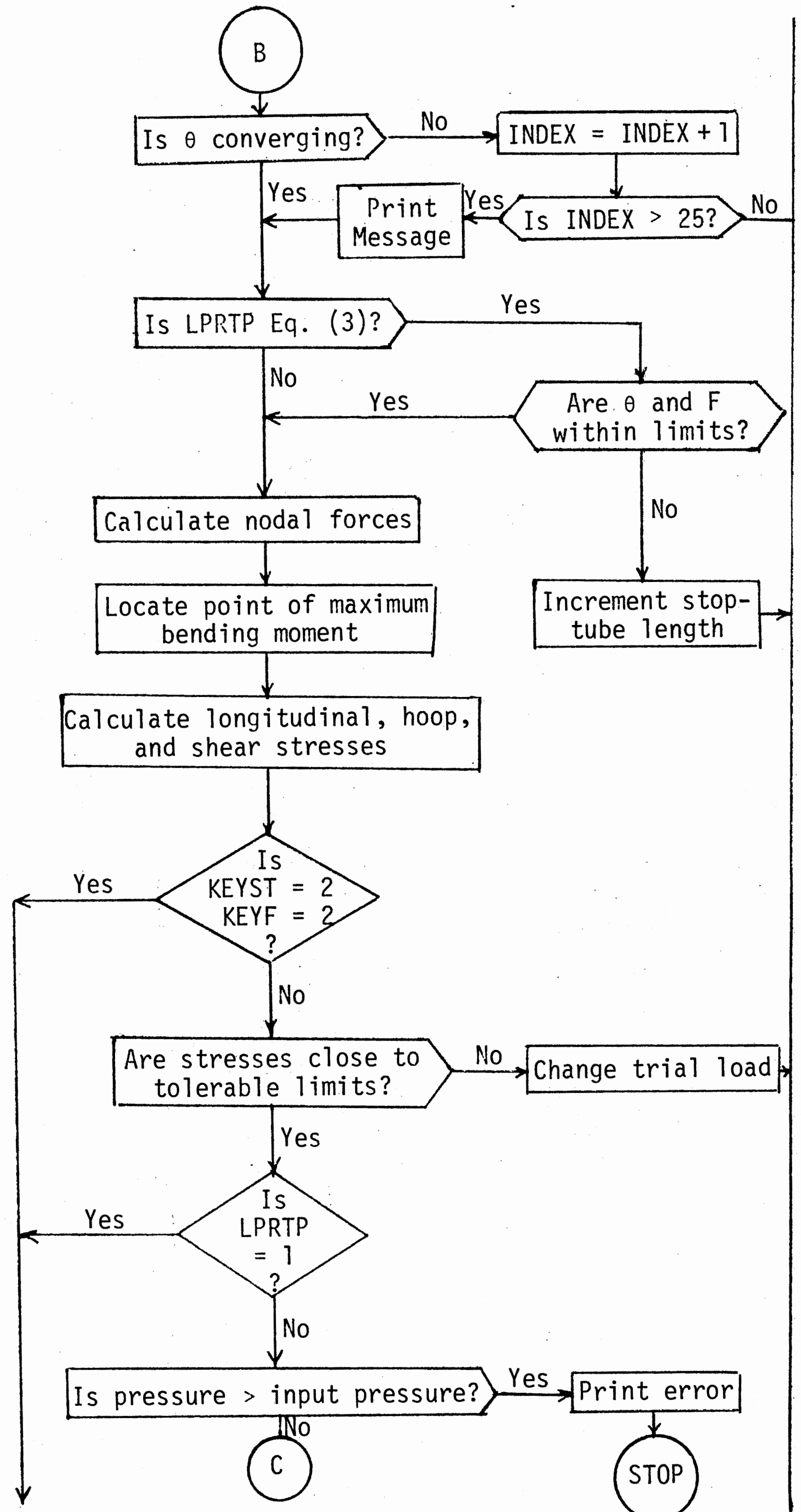


Figure 9. (Continued)

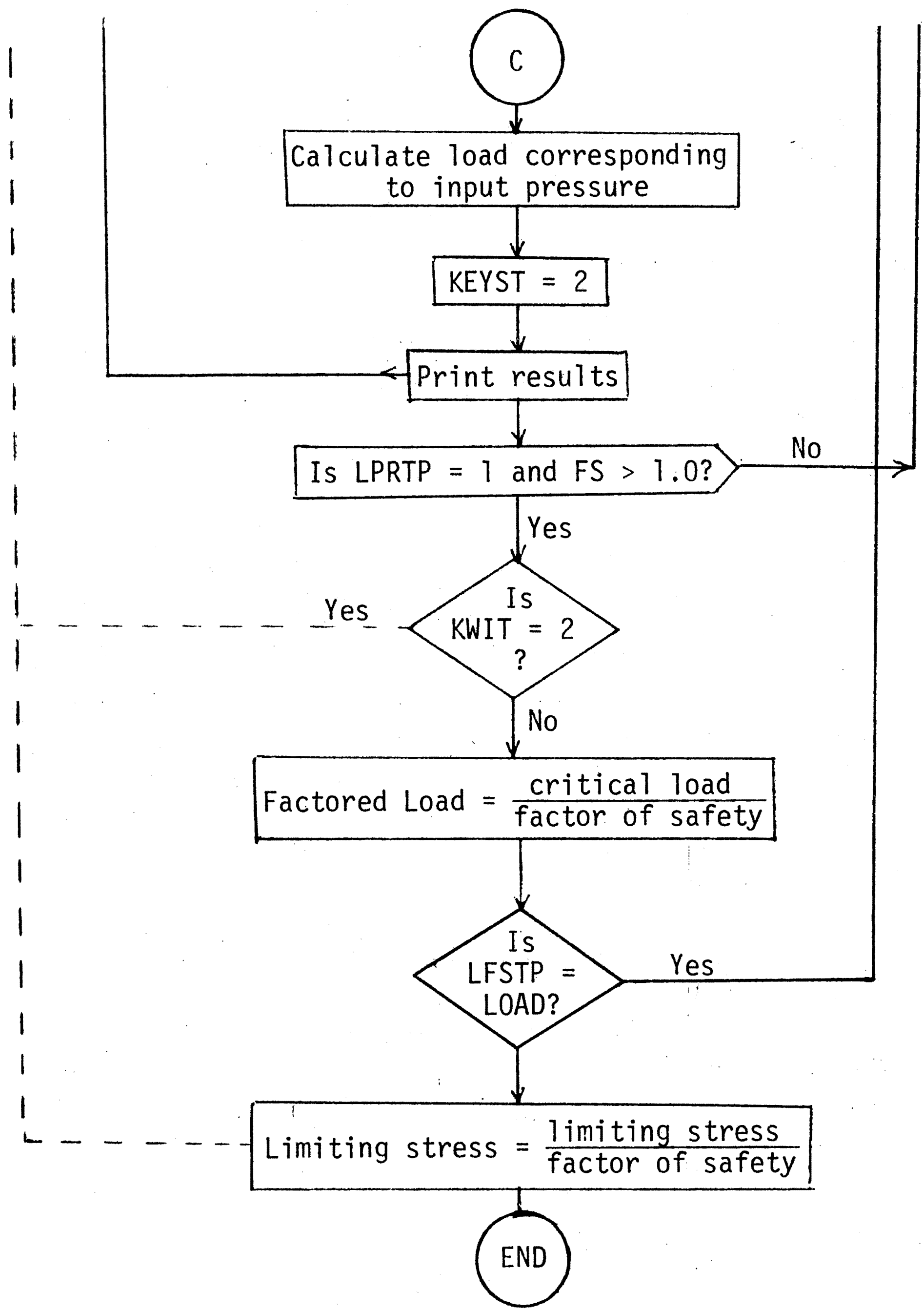


Figure 9. (Continued)

4.1 Subprogram Operation

4.1.1 DRIVER

The DRIVER routine sets up the maximum storage, maximum dimensions, and number of elements permitted in the program. It calls subroutine SACFI to perform the analysis of the hydraulic cylinder.

4.1.2 SACFI

SACFI is the executive subroutine for the complete program. This subroutine sets up all iterative control keys and calls other subroutines to perform the required operations.

4.1.3 INECHO

Subroutine INECHO reads and echoprints all input data. The subroutine checks the input data at several stages for proper input and if any error in the input is encountered during the execution, the program terminates and prints an error message. Two options, AUTO and SELF, aid in generating node numbers and coordinates. The AUTO option generates node numbers automatically and in the SELF option node numbers and coordinates are supplied as input data. The SELF option is useful when it is necessary to have a refined mesh in certain regions of the hydraulic cylinder. In general, required data input are the dimensions of the cylinder parts, support conditions, loading eccentricities, friction coefficients at the supports, and self-weights of the various parts of the cylinder.

4.1.4 DIST

Subroutine DIST generates the nodal data, depending on the options used in INECHO. It also distributes the material properties and elastic restraints at the supports.

4.1.5 CONST

Subroutine CONST calculates constant quantities used in the calculation, such as the stiffnesses of bearings and seals, cross-section properties of the cylinder, friction moments, and hoop stress coefficients.

4.1.6 TRIALP

TRIALP calculates the initial load and load increments necessary for the iterative process. The trial load is the smaller of the buckling load obtained by considering the stiffness of the whole cylinder to be that of the rod and the load that causes the cylinder to fail by hoop stress. In the case of hollow pressurized rods, the load causing hoop stress failure in the rod region is also considered in the above comparison.

4.1.7 EQSTIF

EQSTIF assembles the overall stiffness matrix, the matrix of nodal forces, and imposes any specified displacements at the nodes by calling the subroutine MOD. For successive iterations in calculating the crookedness angle, subroutine EQSTIF formulates the constraint equations at the gland. The function of the subroutine is to assemble the overall stiffness matrix and nodal force matrix as in Equation (3.15).

4.1.8 STIFF

Subroutine STIFF generates the stiffness matrix for each element and calculates nodal forces due to the self-weight.

4.1.9 MOD

Subroutine MOD modifies the overall stiffness matrix to impose any specified nodal displacements.

4.1.10 MULT

Subroutine MULT performs multiplication of two matrices.

4.1.11 BANSOL

Subroutine BANSOL solves the system of simultaneous equations (Equation (3.15)) for the unknown displacements {U}. Gauss elimination is used for solution of the simultaneous equations.

4.1.12 THETA

Subroutine THETA calculates the crookedness angle at the gland for any particular value of the gland moment. This subroutine calculates the forces acting on the bearings by calling GFORCE. Subroutine THETA also locates the position of the step point C (Figure 6) for any particular value of the crookedness angle.

4.1.13 GFORCE

Subroutine GFORCE calculates the forces on the seals and bearings for a particular value of the crookedness angle.

4.1.14 GLAFOR

Subroutine GLAFOR calculates the value of gland moment for a particular value of the crookedness angle. This value of the gland moment is in turn used to calculate a new value of the crookedness angle.

4.1.15 FORCES

Subroutine FORCES calculates the nodal forces in the finite element model.

4.1.16 STOPTB

Subroutine STOPTB determines the required length of a stop-tube by incrementing the length of the stop-tube and checking the crookedness angle and lateral forces on the bearings and seals against the limiting values.

4.1.17 MAXMOM

Subroutine MAXMOM determines the locations in the cylinder and the rod at which the bending moment is maximum.

4.1.18 STRESS

Subroutine STRESS calculates the maximum longitudinal stress, maximum hoop stress, and maximum shear stress, and compares them with the limiting values. It then makes any necessary change in the trial load using the trial load increments.

4.1.19 OUTPUT

Subroutine OUTPUT prints all results necessary in the design of hydraulic cylinders, such as the maximum load carrying capacity, type of failure, magnitude of stresses, and factors of safety existing for these stresses, magnitudes of the forces on the bearings and seals, crookedness angle, and magnitude of deflections.

4.2 Example Problems

In order to verify the accuracy of the method of analysis and to demonstrate the use of the computer program, several problems have been solved and results have been compared with other investigations.

4.2.1 Problem SACFI1

SACFI1 is an example problem for the analysis of hydraulic cylinders under the following loading conditions and analysis options.

1. Vertical hydraulic cylinder (no self-weight), pinned at both ends, and no eccentricity.
2. Horizontal cylinder, no eccentricity.
3. Horizontal cylinder, eccentricity on the rod side = +0.5 inches (along the Y axis).
4. Horizontal cylinder, eccentricity on the rod side = -0.5 inches (along the Y axis).
5. Analysis for given operating pressure = 2 ksi.
6. Analysis to determine stop-tube length.

The details of the cylinder considered in the example are shown in Table I (Appendix C).

The above problems were solved using SACREG (10) and the results are summarized in Figure 10. There is a slight difference in the ultimate load in cases where the self-weight is acting because of differences in assumptions regarding the self-weight distribution at the gland.

4.2.2 Comparison of Results With Experimental Investigation

In the following section of this study the analytical procedure

Case	Problem Description	Critical Load Reference (10) SACREG	 Present Study SACFI
I	No eccentricity and no self-weight	78.63 K	78.63 K
II	No eccentricity and self-weight	25.74 K	25.82 K
III	Positive eccentricity = +0.5 in.	18.58 K	18.72 K
IV	Negative eccentricity = -0.5 in.	24.59 K	24.35 K
V	Analysis for operating pr = 2 ksi	14.33 K	14.33 K
VI	Analysis for length of stop-tube Critical fluid pressure = 3 ksi Maximum limit on bearing forces = 3 kips Maximum allowable crookedness angle = 0.0075 rad.	2.00 in.	2.00 in.

Figure 10. Problem SACFI1

developed herein is compared with the experimental response of hydraulic cylinders (11). The earlier work was primarily directed toward assessing the accuracy of the model of the rod/cylinder interfact in predicting the actual behavior of the real system. The effort involved was:

1. Subjecting fluid power cylinders to controlled loading situations and measuring the response of each cylinder. All cylinders were loaded laterally by applying equal loads equidistant from the supports. A direct reading dial indicator was used to measure the deflection of the system at the interface. Values of load and interface deflections were recorded simultaneously for each increment of load. The maximum lateral load applied to each cylinder produced the same bending moment at the interface as that predicted by the computer program for ultimate axial load.

2. Performing analyses of these cylinders with

    a. The computer program described in Reference (10) using dimensional and material properties furnished by the manufacturer.

    b. Analyzing the hydraulic cylinder as a continuous beam, assuming that crookedness angle at the gland is absent.

3. Comparing experimental results, analytical results including the effect of the crookedness angle (10), and the results, assuming the rod/cylinder interface to be continuous.

In this section the analytical procedure followed in the present study is also included in the above comparisons.

The cylinders which were investigated are described in Appendix C (Tables I through VIII). In all cases the cylinders were regular, single stage units. The manufacturer's drawings and specifications were used in determining the values of parameters used in the analysis.

Experimental and analytical results are presented in Figures 11 through 18. In these graphs bending moments have normalized by dividing the maximum applied moment. Deflections have been normalized by dividing by the measured deflection at maximum applied moment.

As the crookedness angle effect is not present in the continuous beam analysis, the predicted deflections are lower than those measured and provide an upper bound on the moment-deflection relationship. For most of the cases the results of the analytical procedure SACREG (10) and the present analysis are very close and provide a lower bound on the experimental result. The present study gives a conservative estimate of the load carrying capacity of the cylinder.

4.2.3 Effect of Eccentricity on the Critical Load

Axial load eccentricity in a hydraulic cylinder reduces its load carrying capacity. In actual practice the eccentric load can be in or out of the plane of self-weights. In the case of eccentric loads acting in an arbitrary plane, not along the plane of self-weights, the eccentricity must be resolved into components along and perpendicular to the direction of self-weight (along the Y and Z axes). The computer program SACFI may be used to analyze cylinders in which the eccentricity may or may not be along the plane of self-weight.

To verify the procedure followed herein, the axial load was applied at the rod end of a vertical cylinder. The eccentricity was kept constant for all cases. As the self-weights are absent in a vertical

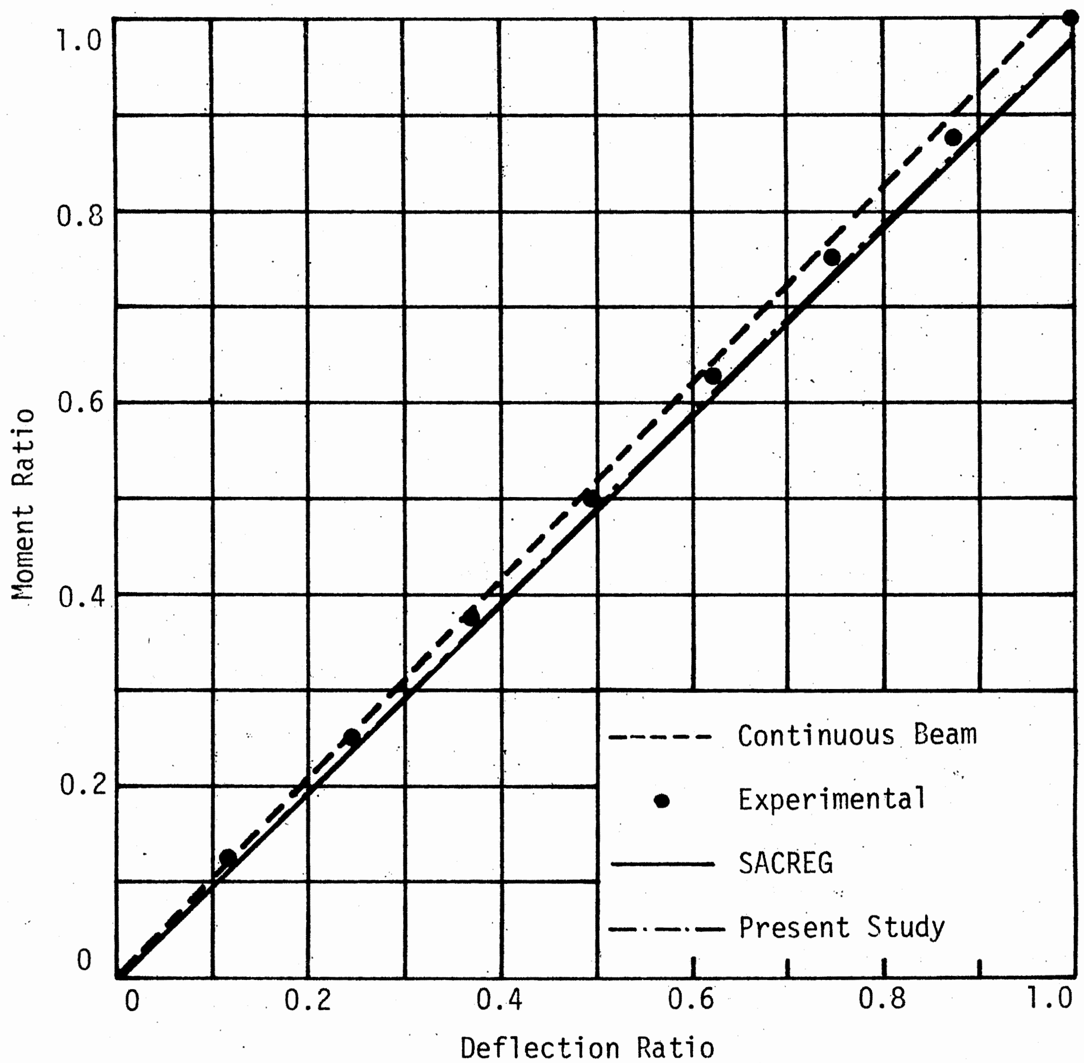


Figure 11. OSU Cylinder No. 1

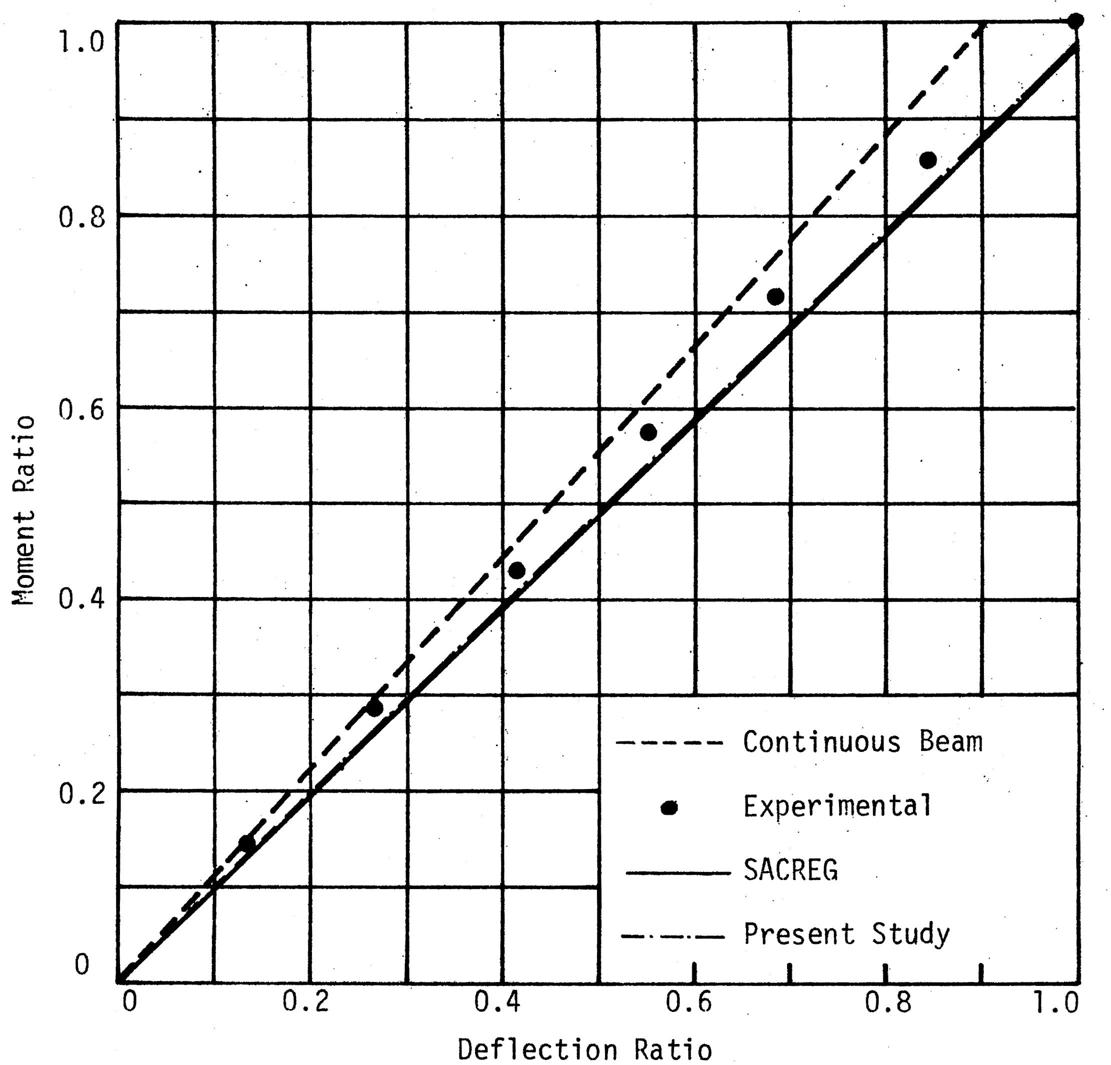


Figure 12. OSU Cylinder No. 2

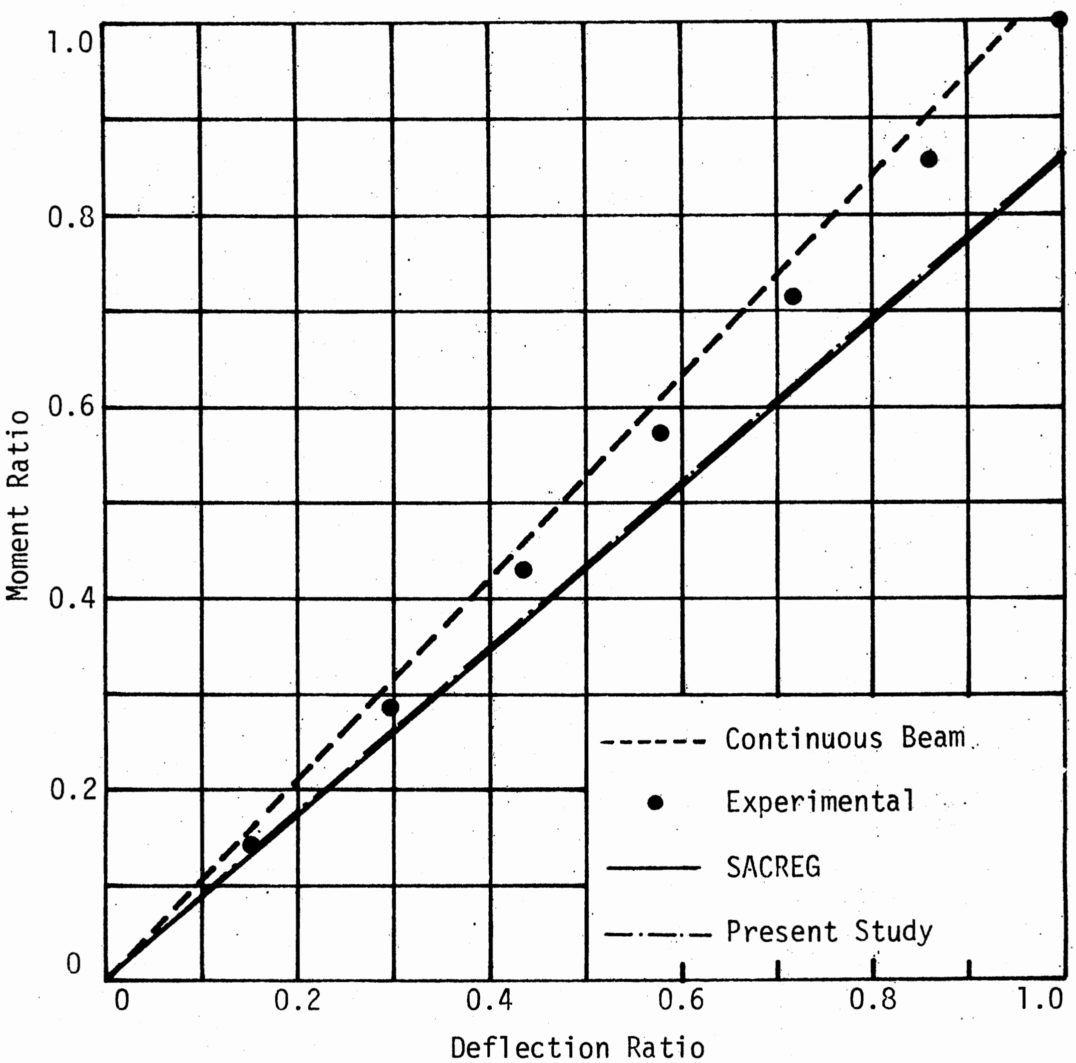


Figure 13. OSU Cylinder No. 3 (Average for Three Cylinders)

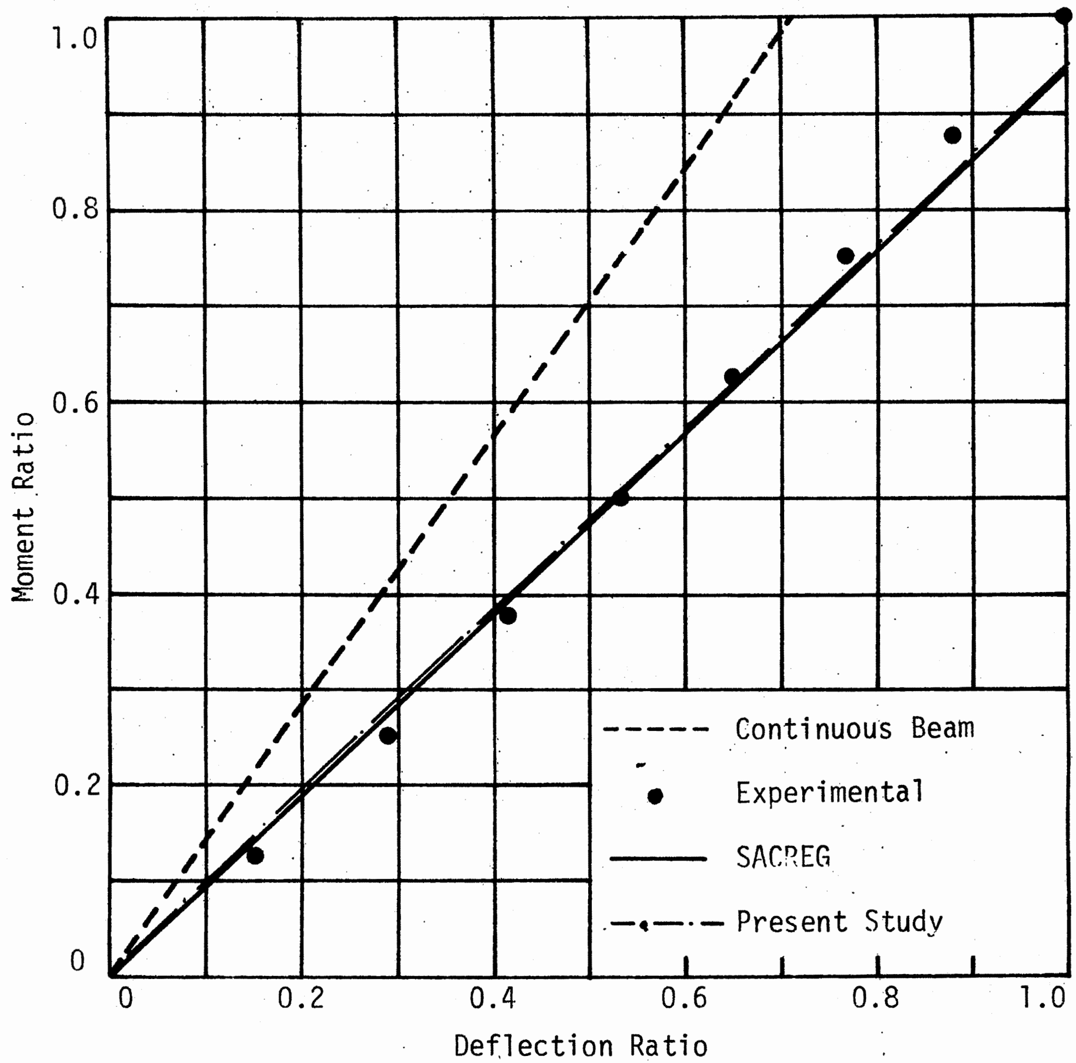


Figure 14. OSU Cylinder No. 4

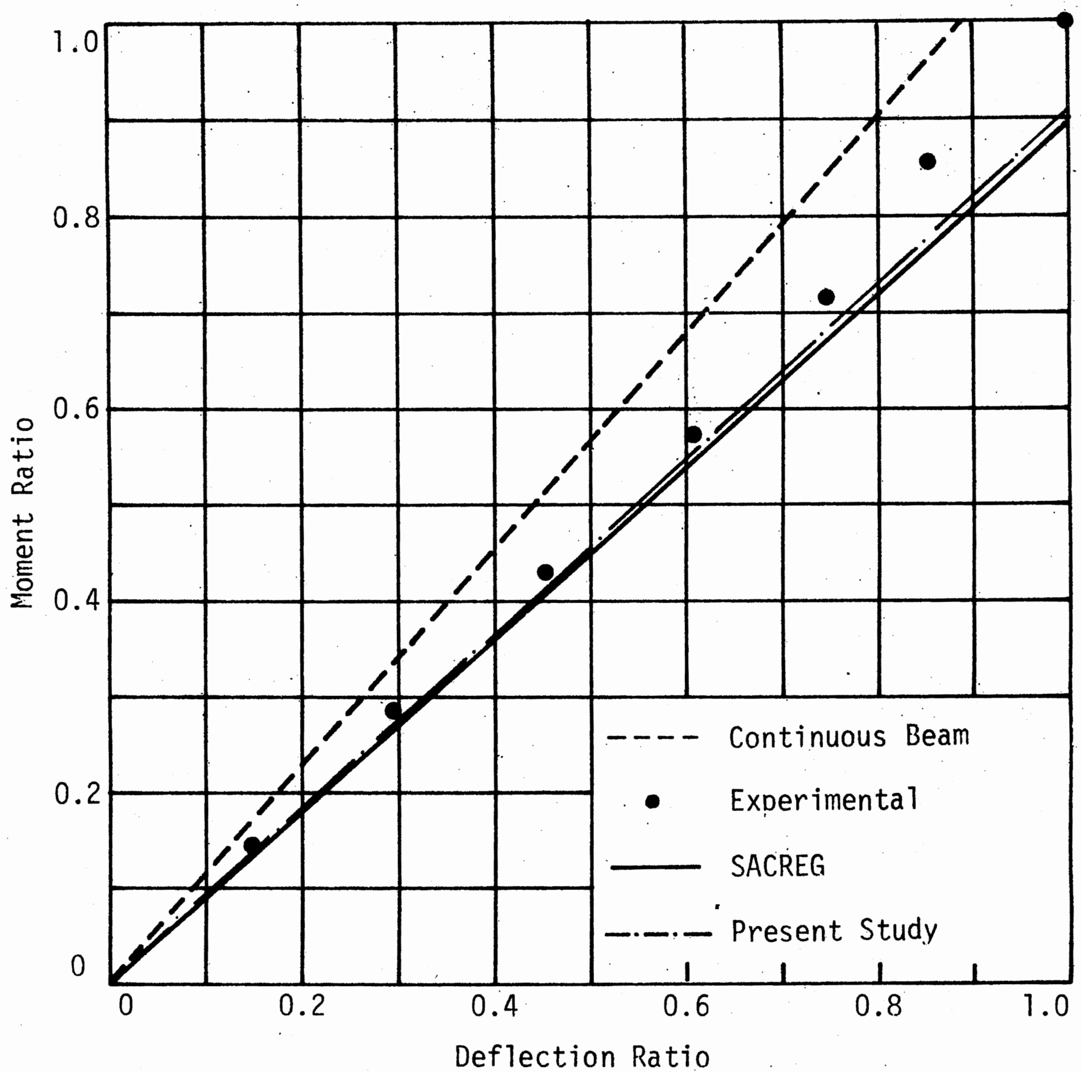


Figure 15. OSU Cylinder No. 5

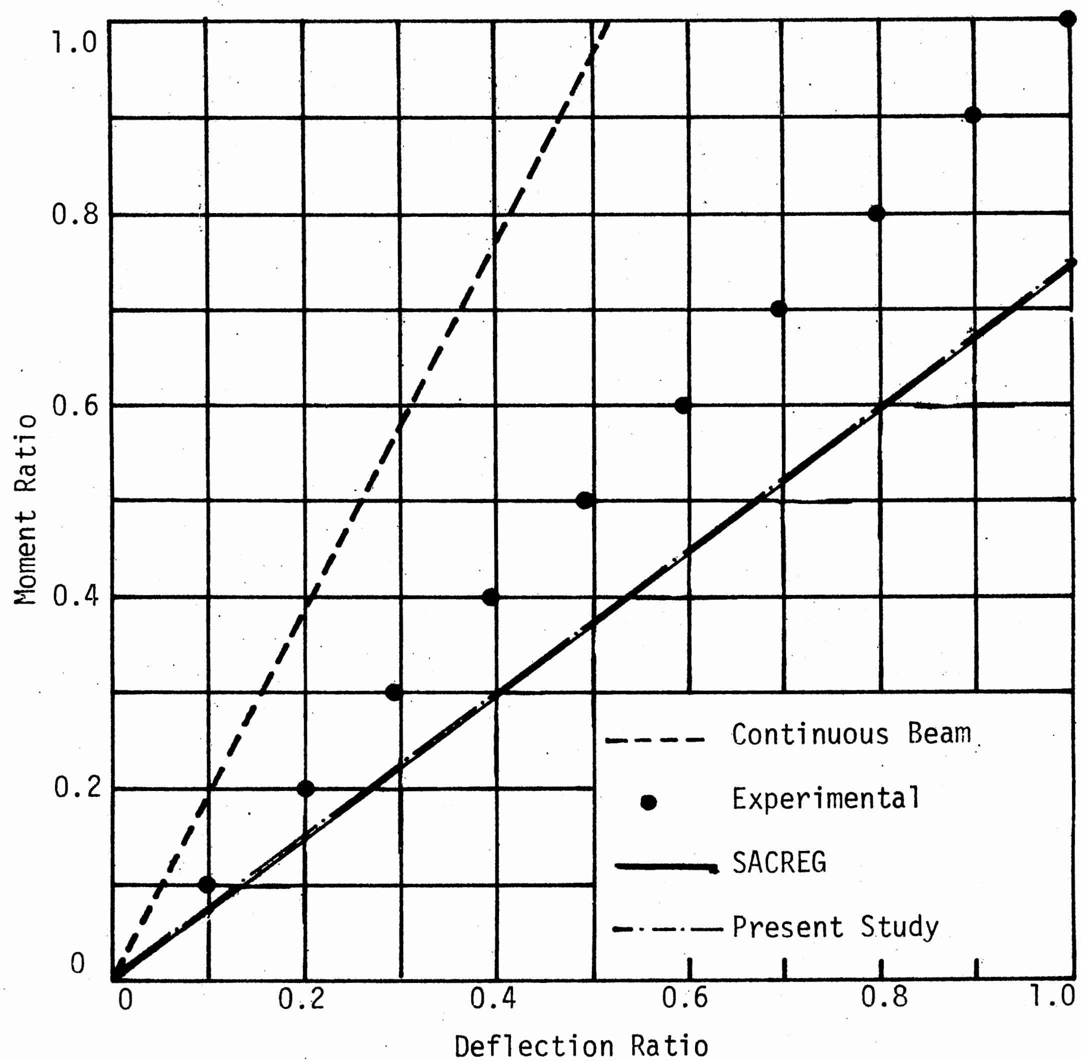


Figure 16. OSU Cylinder No. 6

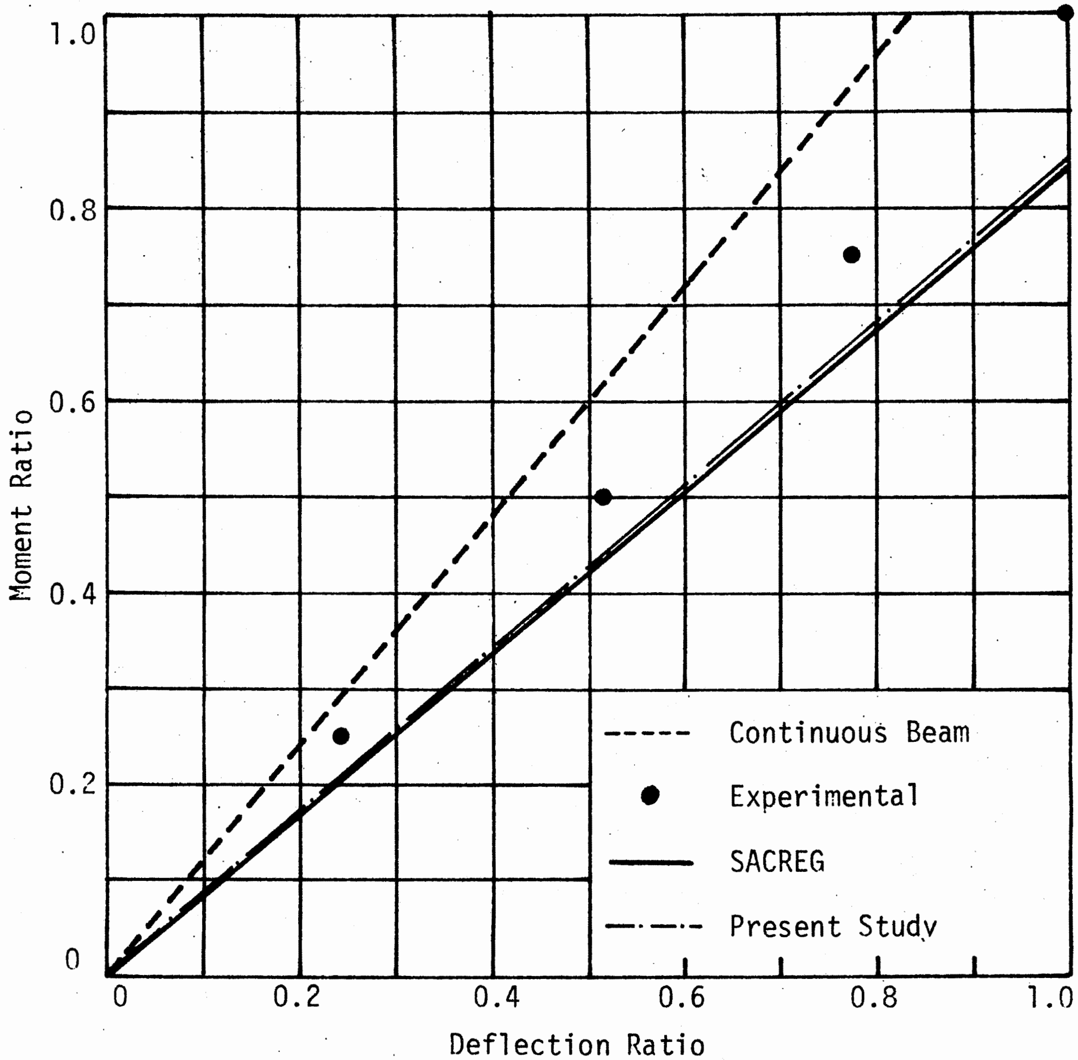


Figure 17. OSU Cylinder No. 7

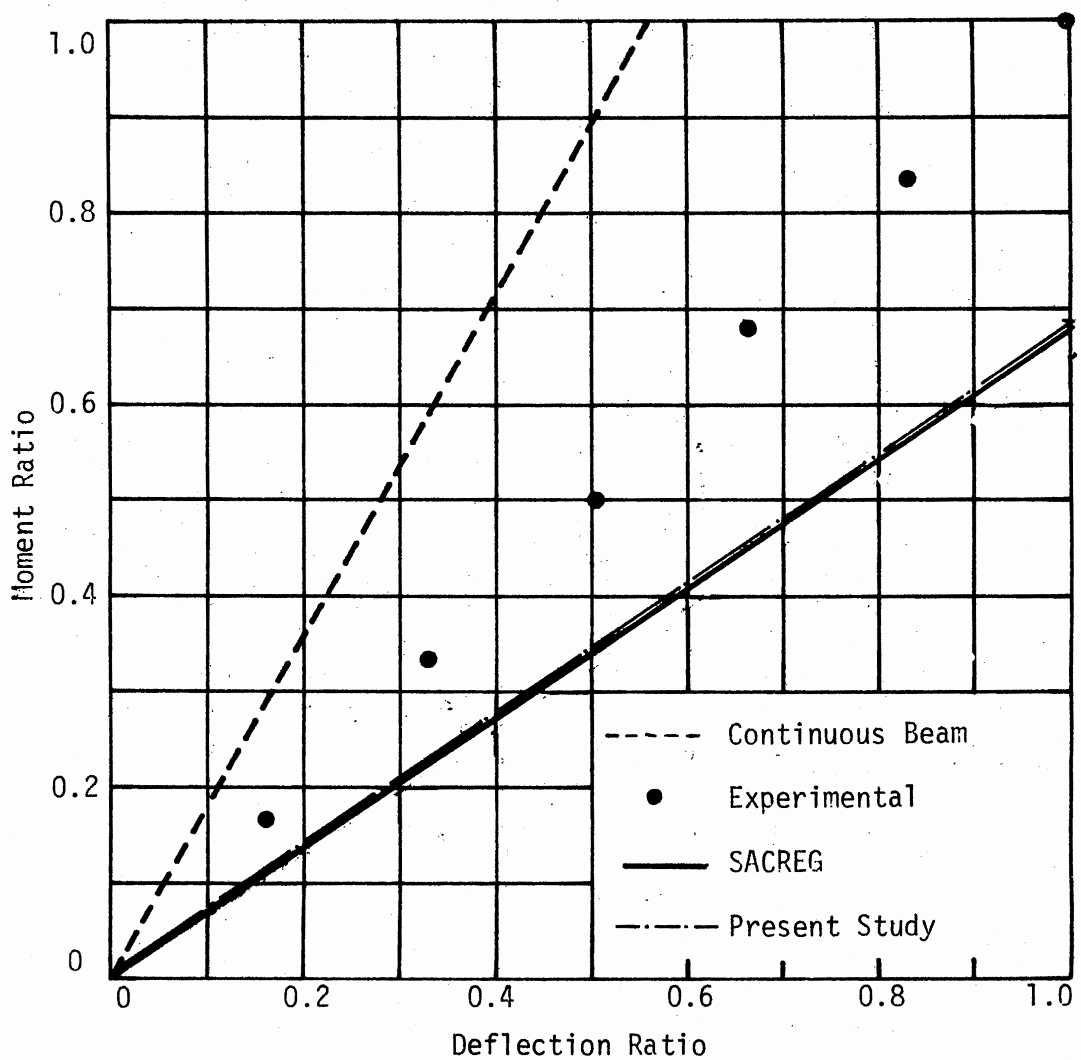


Figure 18. OSU Cylinder No. 8 (Average for Two Cylinders)

cylinder, an accurate solution necessitates that the critical load be the same for all cases. The details of the cylinder used in the example are given in Table I, and an eccentricity of one inch at the rod end was applied at different combinations of eccentricities in the Y and Z directions. In all cases the critical load was found to be 17.05 kips.

Problem SACFI2 illustrates the application of the computer program to problems with eccentricities in arbitrary directions and also shows the effect of the eccentricity on the load carrying capacity of the cylinder.

A hydraulic cylinder, OSU No. I (Table I, Appendix C) is analyzed in a horizontal position with pin supports at both ends. The axial load P is assumed to act at an eccentricity e_y along a radial direction, as shown in Figure 19. e_y and e_z are the eccentricities in the Y and Z directions, respectively. The position of the axial load is defined by

$$\phi = \tan^{-1} \frac{e_z}{e_y}$$

where ϕ is measured from the positive Y axis. For the cylinder under consideration, an eccentricity of one inch was applied at the rod end at different values of ϕ. The results are tabulated in Figure 20.

The tabulation listed in Figure 20 indicates that positive axial load eccentricities ($0 < \phi < 90$) reduce the ultimate load carrying capacity of the cylinder. For these eccentricities the moments due to the self-weight and the eccentricity are additive. For axial loads applied with negative eccentricity ($90 < \phi < 180$), the effect of the self-weight is opposite to that of the eccentric loading and, hence, there is a corresponding slight increase in the critical load.

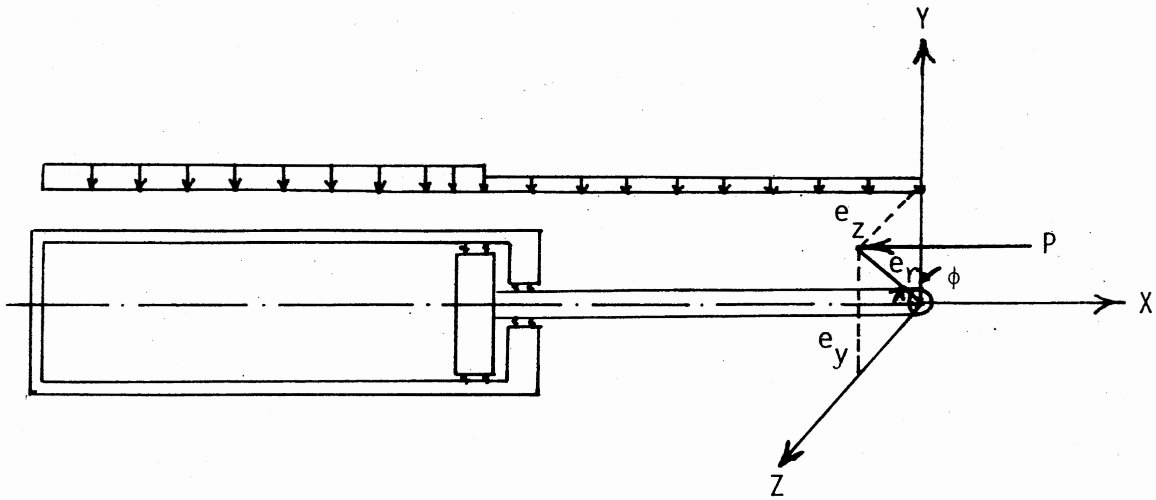


Figure 19. Hydraulic Cylinder Subjected to an Axial Load Not in the Plane of Self-Weight

Eccentricity Along Y Axis (in.)	Eccentricity Along Z Axis (in.)	ϕ	Critical Load (kips)
1.0000	0.0000	0°	15.13
0.7071	0.7071	45°	15.60
0.0000	1.0000	90°	16.80
-0.7071	0.7071	135°	18.07
-1.0000	0.0000	180°	18.35

Figure 20. Tabulation of Critical Load at Various Positions of the Eccentric Load

4.2.4 Analysis of Vertical Lift Cylinders

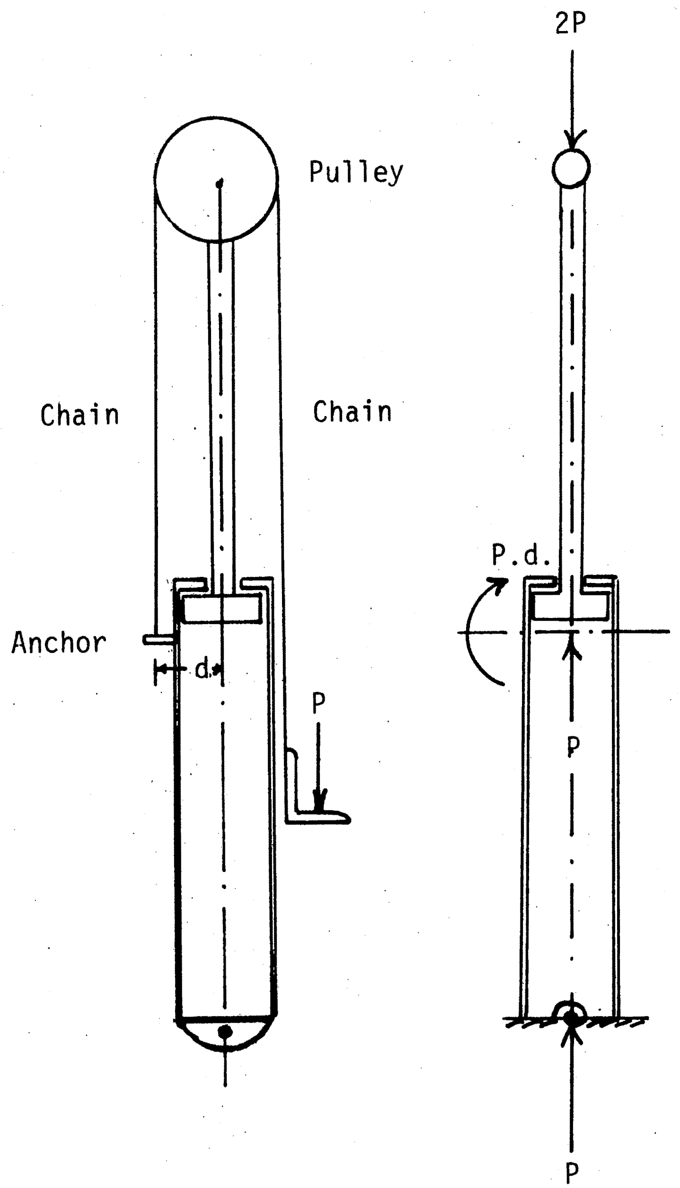
To illustrate the generality of the method, the load carrying capacity of a vertical lift cylinder is determined in this example problem. A lift cylinder (Figure 21(a)) is a regular cylinder with a chain anchor welded to the cylinder port. The lift chains hook to the chain anchors at one end and pass over the pulley supported at the rod end and carry the carriage assembly at the other end.

When a load P is lifted by the carriage assembly, an axial force 2P results in the cylinder and a tension P is produced in the chain. The force P in the chain is transferred to the cylinder at the chain anchor. This force P can be replaced by an axial force P and a moment Pd, as shown in Figure 21(b).

The analysis was performed using OSU Cylinder I (Table I, Appendix C) and the distance between the chain anchor and the cylinder axis was taken as five inches. The load carrying capacity for the cylinder was found to be 10.5 kips. The input data for problem SACFI3 are shown in Appendix D.

4.2.5 Example Problem SACFI4

Example problem SACFI4 illustrates all the options and wide range of possible variations in the input data in program SACFI. The input data listing is included with the results in Appendix D.



(a) Load Carrying Action of a Vertical Lift Cylinder

(b) Equivalent Force System

Figure 21. Vertical Lift Cylinder

CHAPTER V

SUMMARY AND RECOMMENDATIONS

The method of analysis presented here replaces the original structure by a model composed of discrete space frame elements. This results in a solution applicable for a more general system of loading and boundary conditions than was available from previous analyses. Because the force-displacement characteristics of the individual elements are based on the closed form solution governing the bending of beams under the effect of axial and lateral loads, the minimum number of elements necessary to represent the hydraulic cylinder geometry given an accurate solution.

The analysis takes into account the crookedness angle at the sliding connection, eccentricity of loading at any point along the cylinder in any arbitrary direction, self-weight of the system, and presence of any external moment anywhere along the cylinder. The analysis is applicable to a wide range of variations, such as hollow and solid rods, with or without fluid pressure, or any number and combination of simple and fixed supports.

Computer program SACFI incorporates the method of analysis, and solutions obtained using the program have compared satisfactorily with known analytical solutions and experimental results. The program has the following options:

1. Determination of the critical load and analysis for a certain factored load.

2. Analysis for a particular fluid pressure.

3. Analysis to determine the required length of the stop-tube.

Future extensions and improvements should be directed toward:

1. Experimental investigation of the hydraulic cylinder to determine the ultimate load carrying capacity and to compare experimental results with the theoretical analysis.

2. Development of the biaxial bending analysis of tie rod and telescopic cylinders using the finite element analysis.

3. Development of design charts and graphs.

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APPENDIX A

ELEMENT STIFFNESS MATRIX

Each individual element considered in the analysis of hydraulic cylinders has eight degrees of freedom, as shown in Figure 6. The force-displacement relation for a typical element is derived below.

A beam element of length L, subjected to an axial load P, and loaded by its self-weight in the negative Y direction is shown in Figure 22. v and β are the translation and rotation displacements, respectively.

The differential equation expressing the bending of beams under axial and lateral loads is given by

$$EIv^{IV} + Pv'' = -q \tag{A.1}$$

where

E = Young's modulus of the material;

I = moment of inertia of the cross section; and

q = self-weight per unit length.

Equation (A.1) can be written as

$$v^{IV} + \frac{\phi^2}{L^2} v'' = -\frac{q}{EI} \tag{A.2}$$

where

$$\phi^2 = \frac{PL^2}{EI}$$

The general solution of Equation (A.2) is

$$v = A\sin\frac{\phi x}{L} + B\cos\frac{\phi x}{L} + \frac{Cx}{L} + D - \frac{qx^2\ell^2}{2\phi^2 EI} \tag{A.3}$$

The boundary conditions which are to be enforced on the solution are

at $x = 0$: $v = v_i$

at $x = L$: $v = v_{i+1}$

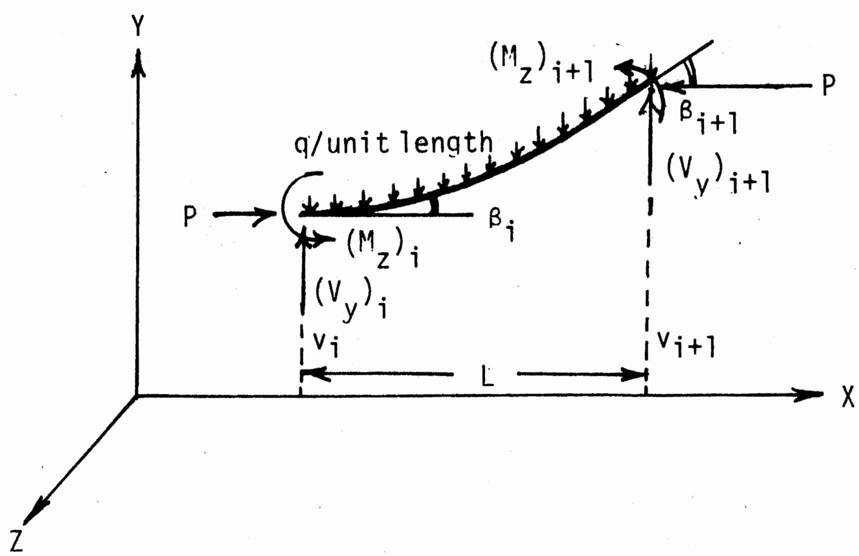

Figure 22. Force System Acting on a Plane Frame Element in the XY Plane

$$\text{at } x = 0: \quad v' = \beta_i$$

$$\text{at } x = L: \quad v' = \beta_{i+1} \tag{A.4}$$

Equation (A.4) results in values for constants as given in Equation (A.5), Figure 23.

Shear forces and moments at ends A and B in the element can be expressed in terms of deflection v as

$$\begin{aligned}
(M_z)_i &= -EIv_i'' \\
(Mz)_{i+1} &= EIv_{i+1}'' \\
(V_y)_i &= EI[v''' - Pv'] \\
(V_y)_{i+1} &= -EI[v''' - Pv']
\end{aligned} \tag{A.6}$$

Combination of Equations (A.5) and (A.6) yields the force-displacement relationship for effects in the XY plane, as shown in Equation (A.7), Figure 24.

Equation (A.7) can be written as shown in Equation (A.8), Figure 25.

The same element subjected to effects in the XZ plane is shown in Figure 26. w and ρ are the translation and rotation displacements. Because it is assumed that the self-weight acts along the negative Y direction, the moments due to the self-weight are absent.

Application of the procedure outlined above allows the force-deformation relationship for this case to be expressed as shown in Equation (A.9). Equations (A.8) and (A.9) can be combined to express the force-deformation relationship for the three-dimensional system as in Equation (3.3), Figure 5.

$$
\begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} = \frac{1}{\Delta_c} \begin{bmatrix} -\phi \mathrm{Sin}\phi & L(1 - \mathrm{Cos}\phi - \phi \mathrm{Sin}\phi) & \phi \mathrm{Sin}\phi & L(\mathrm{Cos}\phi - 1) \\ \phi(1 - \mathrm{Cos}\phi) & L(\mathrm{Sin}\phi - \phi \mathrm{Cos}\phi) & \phi(\mathrm{Cos}\phi - 1) & L(\phi - \mathrm{Sin}\phi) \\ \phi^2 \mathrm{Sin}\phi & L\phi(1 - \mathrm{Cos}\phi) & -\phi^2 \mathrm{Sin}\phi & L\phi(1 - \mathrm{Cos}\phi) \\ \phi(1 - \mathrm{Cos}\phi - \phi \mathrm{Sin}\phi) & L(\phi \mathrm{Cos}\phi - \mathrm{Sin}\phi) & \phi(1 - \mathrm{Cos}\phi) & L(\mathrm{Sin}\phi - \phi) \end{bmatrix} \begin{bmatrix} v_i \\ \beta_i \\ v_{i+1} \\ \beta_{i+1} \end{bmatrix} - \frac{1}{\Delta_c} \begin{bmatrix} \frac{q\ell^4}{2\phi^2 EI}(2 - 2\mathrm{Cos}\phi - \phi \mathrm{Sin}\phi) \\ \frac{q\ell^4}{2\phi^2 EI}(2\mathrm{Sin}\phi - \phi \mathrm{Cos}\phi - \phi) \\ \frac{q\ell^4}{2\phi^2 EI}(2\phi \mathrm{Cos}\phi + \phi^2 \mathrm{Sin}\phi - 2\phi) \\ \frac{q\ell^4}{2\phi^2 EI}(\phi + \phi \mathrm{Cos}\phi - 2\mathrm{Sin}\phi) \end{bmatrix} \tag{A.5}
$$

where

$$\Delta_c = \phi(2 - 2\mathrm{Cos}\phi - \phi \mathrm{Sin}\phi)$$

Figure 23. Equation for Constant A, B, C, and D

$$
\begin{bmatrix} (V_y)_i \\ (M_y)_i \\ (V_y)_{i+1} \\ (M_y)_{i+1} \end{bmatrix} = \frac{EI}{L^3\Delta_c} \begin{bmatrix} \phi^4 \mathrm{Sin}\phi & L\phi^3(1-\mathrm{Cos}\phi) & -\phi^4 \mathrm{Sin}\phi & L\phi^3(1-\mathrm{Cos}\phi) \\ L\phi^3(1-\mathrm{Cos}\phi) & L^2\phi^2(\mathrm{Sin}\phi-\phi\mathrm{Cos}\phi) & L\phi^3(\phi-1) & L^2\phi^2(\phi-\mathrm{Sin}\phi) \\ -\phi^4 \mathrm{Sin}\phi & L\phi^3(\mathrm{Cos}\phi-1) & \phi^4 \mathrm{Sin}\phi & L\phi^3(\mathrm{Cos}\phi-1) \\ L\phi^3(1-\mathrm{Cos}\phi) & L^2\phi^2(\phi-\mathrm{Sin}\phi) & L\phi^3(\mathrm{Cos}\phi-1) & L^2\phi^2(\mathrm{Sin}\phi-\ \mathrm{Cos}\phi) \end{bmatrix} \begin{bmatrix} v_i \\ \beta_i \\ v_{i+1} \\ \beta_{i+1} \end{bmatrix} + \begin{bmatrix} \frac{q\ell}{2} \\ \frac{q\ell^2}{\phi^2} - \frac{q\ell^2}{2\Delta_c}(2\mathrm{Sin}\phi-\phi\mathrm{Cos}\phi-\phi) \\ \frac{q\ell}{2} \\ \frac{q\ell^2}{2\Delta_c}(2\mathrm{Sin}\phi-\phi\mathrm{Cos}\phi-\phi)\mathrm{Cos}\phi + \frac{q\ell^2}{2\phi}\ \mathrm{Sin}\phi - \frac{q\ell^2}{\phi^2} \end{bmatrix} \tag{A.7}
$$

Figure 24. Force-Deformation Relation in the XY Plane

$$\begin{bmatrix} (V_y)_i \\ (M_z)_i \\ (V_y)_{i+1} \\ (M_z)_{i+1} \end{bmatrix} = \begin{bmatrix} T & R & -T & R \\ R & S & -R & CS \\ -T & -R & T & -R \\ R & CS & -R & T \end{bmatrix} \begin{bmatrix} v_i \\ \beta_i \\ v_{i+1} \\ \beta_{i+1} \end{bmatrix} + \begin{bmatrix} \frac{q\ell}{2} \\ \frac{q\ell^2}{\phi^2} - \frac{q\ell^2}{2\Delta_c}(2\mathrm{Sin}\phi - \phi\mathrm{Cos}\phi - \phi) \\ \frac{q\ell}{2} \\ \frac{q\ell^2}{2\phi}\mathrm{Sin}\phi + \frac{q\ell^2}{2\Delta_c}\mathrm{Cos}\phi(2\mathrm{Sin}\phi - \phi\mathrm{Cos}\phi - \phi) - \frac{q\ell^2}{\phi^2} \end{bmatrix} \qquad \text{(A.8)}$$

where

$$T = \frac{4EI}{L^3}\left[2K(1 + C) - \frac{\phi^2}{4}\right] \qquad C = \frac{\alpha}{2\lambda}$$

$$R = \frac{4EI}{L^2}(K(1 + C)) \qquad \beta = \frac{3(1 - \phi\mathrm{Cot}\phi)}{\phi^2}$$

$$S = K\,\frac{4EI}{L} \qquad \alpha = \frac{-6(1 - \phi\mathrm{Cosec}\phi)}{\phi^2}$$

$$\phi^2 = \frac{PL^2}{EI} \qquad \Delta_c = \phi(2 - 2\mathrm{Cos}\phi - \phi\mathrm{Sin}\phi)$$

$$K = \frac{3\lambda}{4\lambda^2 - \alpha^2}$$

Figure 25. Consolidated Force-Deformation Relation in the XY Plane

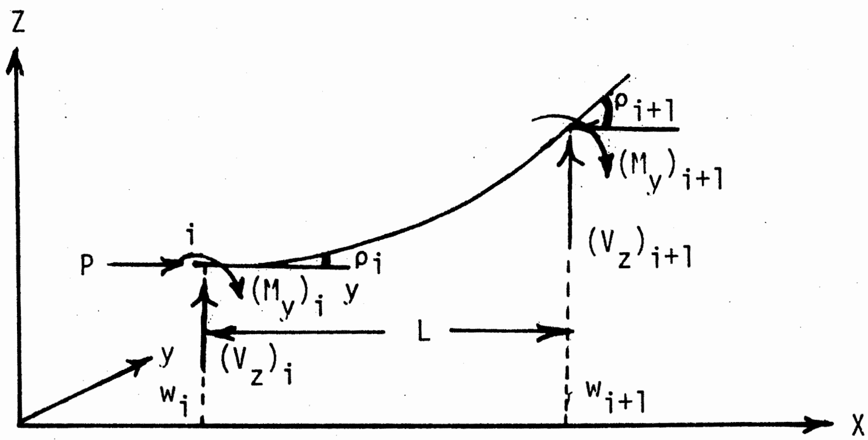

Figure 26. Force System Acting on a Plane Frame in the XZ Plane

$$\begin{bmatrix} (V_z)_i \\ (M_y)_i \\ (V_z)_{i+1} \\ (M_y)_{i+1} \end{bmatrix} = \begin{bmatrix} T & -R & -T & -R \\ -R & S & R & CS \\ -T & R & T & R \\ -R & CS & R & S \end{bmatrix} \begin{bmatrix} w_i \\ p_i \\ w_{i+1} \\ p_{i+1} \end{bmatrix} \tag{A.9}$$

APPENDIX B

CROOKEDNESS ANGLE DETERMINATION

General Discussion of the Crookedness Angle

The effect of the crookedness angle at the sliding connection is included in the present study. The relationship between the moment and crookedness angle as formulated by Seshasai (10)* is reproduced here.

The sliding connection at the rod-cylinder interface in a fluid power cylinder introduces an angular deflection at the interface due to the presence of seals and bearings. This angular deflection increases with increasing applied load.

Two types of seals commonly used in hydraulic cylinders are dynamic and static seals. Dynamic seals prevent the hydraulic fluid from penetrating between two cylinder parts, which translate with respect to one another. Piston seals and rod seals are examples of dynamic seals. Static seals are used at many points between two static surfaces, for example, cylinder and end cap or cylinder and head. Rod bearings are provided to give adequate support and rigidity for the rod. Some common seal materials are nitrile, butyl, ethylene propylene, neoprene, polyurethane, silicone, and tetra fluro ethylene. The bearing materials are , in general, bronze, cast iron, and steel. These seals and bearings are modeled as linear springs in the present analysis.

As the cylinder deflections increase with loading, the lateral load on the bearings and seals increases. Due to the compression of the bearings, a crookedness angle develops at the interface. As explained earlier, the relationship between the moment and the crookedness angle is

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*K. L. Seshasai, "Stress and Deflection Analysis of Regular, Telescoping and Tie Rod Cylinders," unpublished Ph.D. thesis, Oklahoma State University, December, 1976.

linear until the occurrence of the first contact point. The contact point may occur either between the rims of the piston head and the cylinder wall or between the stuffing box and the rod. The contact point introduces a kinematic restraint and a lateral force develops at the point of contact. Further increase in the crookedness angle terminates when two kinematic constraints develop due to the occurrence of two contact points.

The moment-crookedness angle relationships derived in the following sections apply to the case in which a kinematic constraint is absent and for the following five cases of contact.

1. Contact at the piston head front edge.
2. Contact at the stuffing box outside edge.
3. Contact at piston head edges.
4. Contact at stuffing box edges.
5. Contact at the piston head front and stuffing box outside edges.

The equations for lateral forces at the bearings and seals and at the contact points are also developed in the following sections.

The line diagram (Figure 27) shows the crookedness angle between the cylinder axis and the rod axis, and the deformation of piston bearings and rod bearings. From the free body diagram,

$$\theta = \frac{\delta_1^p}{X^p + X_1^p} = \frac{\delta_2^p}{X^p + X_2^p} = \cdots = \frac{\delta_M^p}{X^p + X_M^p}$$

$$= \frac{\delta_1^r}{X^r + X_1^r} = \frac{\delta_2^r}{X^r + X_2^r} = \cdots = \frac{\delta_N^r}{X^r + X_N^r} \qquad (B.1)$$

where

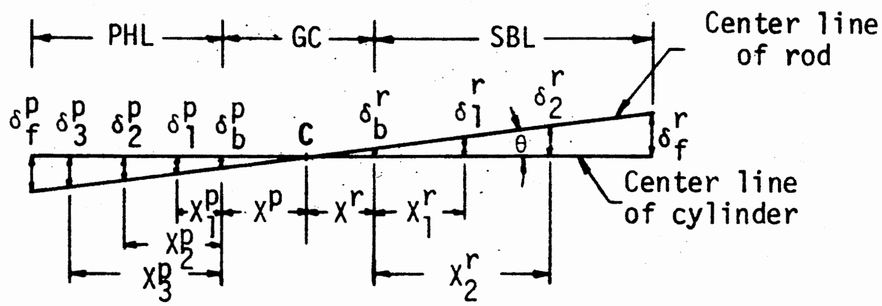

Figure 27. Deformations of Bearings and Seals

$\delta_i^p, i = 1$ to M are the deformations in the piston head bearings;

$\delta_i^r, i = 1$ to N are the deformations in the rod bearings;

$X_i^p, i = 1$ to M are the distances of the piston head bearings from the piston head backface (see Figure 28);

$X_i^r, i = 1$ to N are the distances of the rod bearings from the stuffing box innerface (see Figure 28);

X^p is the distance of the piston head backface from step point C; and

X^r is the distance of the stuffing box innerface from step point C.

The bearings and seals are modeled as linear springs, hence

$$\delta_i^p = \frac{F_i^p}{K_i^p} ; \quad i = 1 \text{ to } M$$

and

$$\delta_i^r = \frac{F_i^r}{K_i^r} ; \quad i = 1 \text{ to } N \tag{B.2}$$

where

F_i^p and F_i^r are the lateral forces on the piston bearings and rod bearings, respectively; and

K_i^p and K_i^r are the stiffnesses of the piston bearings and rod bearings, respectively, which are modeled as linear springs.

Equations (B.1) and (B.2) are combined to obtain

$$\begin{aligned}\theta &= \frac{F_1^p}{K_i^p \cdot (X^p + X_1^p)} = \frac{F_2^p}{K_2^p \cdot (X^p + X_2^p)} = \; . \; . \; . = \frac{F_M^p}{K_M^p \cdot (X^p + X_M^p)} \\ &= \frac{F_1^r}{K_1^r \cdot (X^r + X_1^r)} = \frac{F_2^r}{K_2^r \cdot (X^r + X_2^r)} = \; . \; . \; . = \frac{F_N^r}{K_N^r \cdot (X^r + X_N^r)}\end{aligned} \tag{B.3}$$

in which X^r and X^p are related by

$$X^r = GC - X^p \tag{B.4}$$

where GC = gland clearance (see Figure 28).

Absence of Kinematic Constraints

The moment across the sliding connection develops lateral forces on only the bearings and seals. Figure 28 shows the crookedness angle and the corresponding forces on the bearings and seals. Summation of vertical forces gives,

$$\sum_{i=1}^{M} F_i^p = \sum_{i=1}^{N} F_i^r . \tag{B.5}$$

These forces are expressed in terms of θ using Equation (B.3) to obtain

$$\sum_{i=1}^{M} K_i^p \cdot X_i^p + X^p \cdot \sum_{i=1}^{M} X_i^p = \sum_{i=1}^{N} K_i^r \cdot X_i^r + GC \cdot \sum_{i=1}^{N} K_i^r - X^p \cdot \sum_{i=1}^{N} K_i^r$$

which may be solved for X^p

$$X^p = \frac{\sum_{i=1}^{N} K_i^r \cdot X_i^r + GC \cdot \sum_{i=1}^{N} K_i^r - \sum_{i=1}^{M} K_i^p \cdot X_i^p}{\sum_{i=1}^{M} K_i^p + \sum_{i=1}^{N} K_i^r} . \tag{B.6}$$

Moments are summed about point C to obtain

$$\sum_{i=1}^{M} F_i^p \cdot (X^p + X_i^p) + \sum_{i=1}^{N} F_i^r \cdot (X^r + X_i^r) = M_G \tag{B.7}$$

where M_G is the bending moment at the sliding connection. The lateral forces in Equation (B.7) are expressed in terms of θ using Equation (B.3), which results in

$$\theta = \frac{M_G}{\sum_{i=1}^{M} K_i^p \cdot (X^p + X_i^p)^2 + \sum_{i=1}^{N} K_i^r \cdot (X^r + X_i^r)^2} \tag{B.8}$$

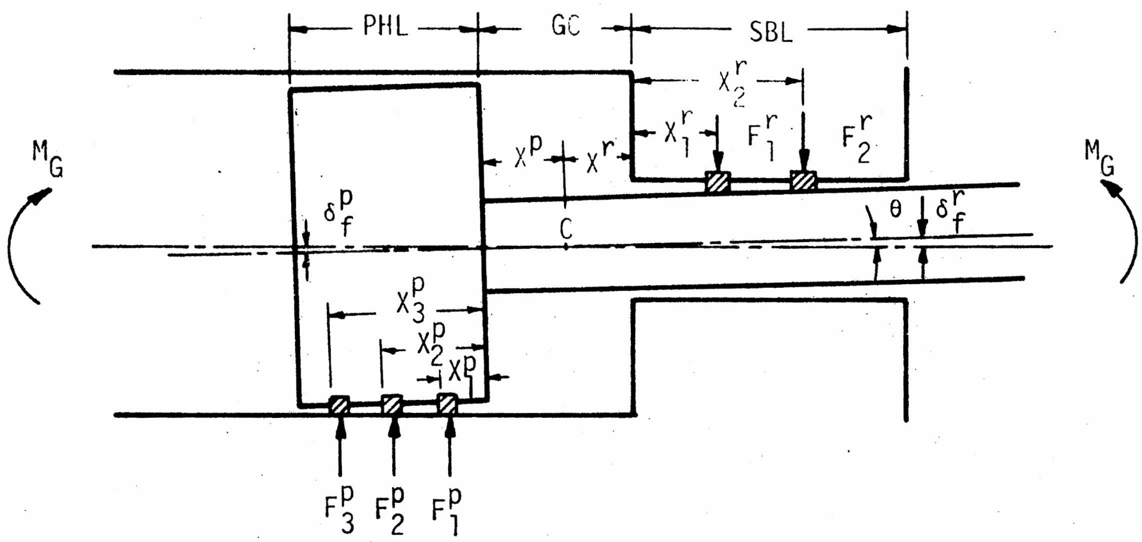

Figure 28. No Metal-to-Metal Contact

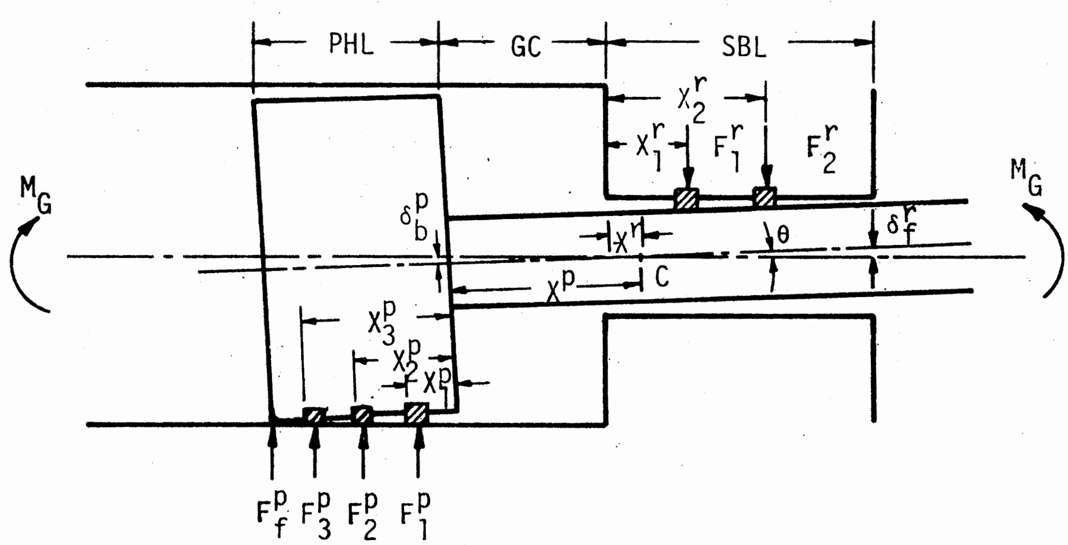

Figure 29. Contact at Piston Head Front Edge

The displacements at the piston head front edge and at the stuffing box outside edge are,

$$\delta_f^p = (X^p + PHL)\cdot\theta \tag{B.9}$$

and

$$\delta_f^r = (X^r + SBL)\cdot\theta \tag{B.10}$$

where

PHL = piston head length; and

SBL = stuffing box length.

For a certain value of moment, if either δ_f^p is greater than PCL (piston clearance from cylinder wall), or δ_f^r is greater than RCL (rod clearance from stuffing box), the next case with one kinematic constraint should be considered. If both the displacements are greater than the corresponding clearances, the proper type of one kinematic constraint case to be used is determined by noting whether δ_f^p exceeds PCL first or δ_f^r exceeds RCL as θ is increased in Equations (B.9) and (B.10). If δ_f^p exceeds PCL, the case with one kinematic constraint at the piston head front edge results, and if δ_f^r exceeds RCL, the case with one kinematic constraint at the outside edge of the stuffing box should be considered.

Presence of One Kinematic Constraint

Contact at the Piston Head Front Edge

The metal-to-metal contact of the front edge of the piston head with the cylinder wall (Figure 29) establishes that

$$\delta_f^p = PCL. \tag{B.11}$$

The crookedness angle is expressed as

$$\theta = \frac{PCL}{X^p + PHL} \qquad \text{(B.12)B}$$

with the sign of the moment at the sliding connection.

Summation of vertical forces gives,

$$F_f^p + \sum_{i=1}^{M} F_i^p = \sum_{i=1}^{N} F_i^r \qquad \text{(B.13)}$$

where F_f^p = lateral contact point force at piston head front edge. Bearing forces in terms of θ, Equation (B.3), are substituted in Equation (B.13), and the equation for the lateral contact point force may be expressed as

$$F_f^p = \theta\cdot\{\sum_{i=1}^{N} K_i^r\cdot X_i^r + GC\cdot\sum_{i=1}^{N} K_i^r - \sum_{i=1}^{M} K_i^p\cdot X_i^p - X^p\cdot(\sum_{i=1}^{M} K_i^p + \sum_{i=1}^{N} K_i^r)\}. \qquad \text{B(B.14)}$$

A summation of moments about the contact point yields

$$-\sum_{i=1}^{M} F_i^p\cdot(PHL - X_i^p) + \sum_{i=1}^{N} F_i^r\cdot(PHL + GC + X_i^r) = M_G \qquad \text{(B.15)}$$

Equations (B.3) and (B.12) are equated to provide

$$F_i^p = \frac{PCL\cdot K_i^p\cdot(X^p + X_i^p)}{X^p + PHL}\ ; \quad i = 1 \text{ to } M$$

and

$$F_i^r = \frac{PCL\cdot K_i^r\cdot(GC - X^p + X_i^r)}{X^p + PHL}\ ; \quad i = 1 \text{ to } N. \qquad \text{(B.16)}$$

Combination of Equations (B.15) and (B.16) results in

$$X^p = \frac{\sum_{i=1}^{N}(GC+X_i^r)\cdot(PHL+GC+X_i^r)\cdot K_i^r - \sum_{i=1}^{M}(PHL-X_i^r)\cdot X_i^r\cdot K_i^r - \frac{M_G\cdot PHL}{PCL}}{\frac{M_G}{PCL} + \sum_{i=1}^{M} K_i^p\cdot(PHL-X_i^p) + \sum_{i=1}^{N} K_i^r\cdot(PHL+GC+X_i^r)} \qquad \text{(B.17)}$$

For all signs to be consistent, PCL must have the same sign as M_G; hence, M_G/PCL is always positive.

The displacements at the piston head back edge and at the stuffing box outside edge are,

$$\delta_b^p = X^p \cdot \theta \tag{B.18}$$

and

$$\delta_f^r = (X^r + SBL) \cdot \theta . \tag{B.19}$$

For a certain value of moment, if either δ_b^p is greater than PCL, or δ_f^r is greater than RCL, the next case with two kinematic constraints should be considered. If both the displacements are greater than the corresponding clearances, the proper case of two kinematic constraints to be used is determined by noting whether δ_b^p exceeds PCL first or δ_f^r exceeds RCL as θ is increased in the Equations (B.18) and (B.19). If δ_b^p exceeds PCL, the case with kinematic constraints at both edges of the piston head should be used, or if δ_f^r exceeds RCL, the case with kinematic constraints at the piston head front edge and at the stuffing box outside edge should be considered.

<u>Contact at the Stuffing Box Outside Edge</u>

The metal-to-metal contact of the stuffing box outside edge with the rod (Figure 30) establishes that,

$$\delta_f^r = RCL \tag{B.20}$$

The crookedness angle is expressed as

$$\theta = \frac{RCL}{GC - X^p + SBL} \tag{B.21}$$

with the sign of the moment at the sliding connection.

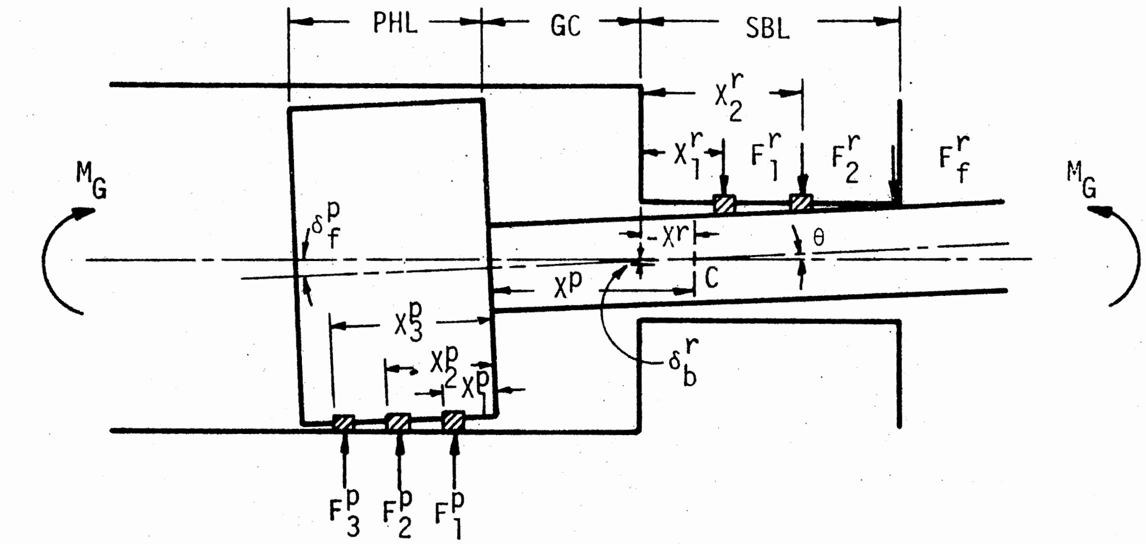

Figure 30. Contact at Stuffing Box Outside Edge

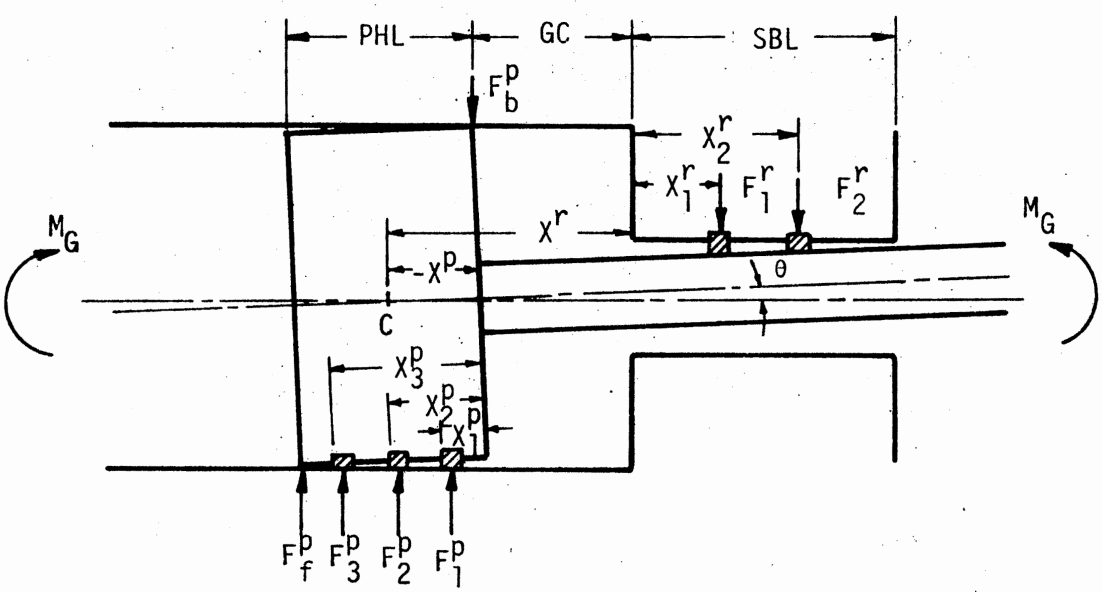

Figure 31. Contact at Piston Head Edges

In the same manner as in the previous case, summation of vertical forces gives,

$$\sum_{i=1}^{M} F_i^p = \sum_{i=1}^{N} F_i^r + F_f^r \tag{B.22}$$

when bearing forces in terms of θ, Equation (B.3) is substituted in Equation (B.22), the lateral contact point force at the stuffing box outside edge is

$$F_f^r = \theta \cdot \{X^p \cdot (\sum_{i=1}^{M} K_i^p + \sum_{i=1}^{N} K_i^r) - (\sum_{i=1}^{N} K_i^r \cdot X_i^r + GC \cdot \sum_{i=1}^{N} K_i^r - \sum_{i=1}^{M} K_i^p \cdot X_i^p)\} \tag{B.23}$$

Moments are summed about the contact point to obtain

$$\sum_{i=1}^{M} F_i^p \cdot (SBL+GC+X_i^p) - \sum_{i=1}^{N} F_i^r \cdot (SBL-X_i^r) = M_G . \tag{B.24}$$

Equations (B.3) and (B.21) are equated to provide

$$F_i^p = \frac{RCL \cdot K_i^p \cdot (X^p + X_i^p)}{GC - X^p + SBL} \; ; \quad i = 1 \text{ to } M$$

and

$$F_i^r = \frac{RCL \cdot K_i^r \cdot (GC - X^p + X_i^r)}{GC - X^p + SBL} \; ; \quad i = 1 \text{ to } N. \tag{B.25}$$

Equation (B.25) is substituted in Equation (B.24) to yield

$$X^p = \frac{\sum_{i=1}^{N} (GC+X_i^r) \cdot (SBL-X_i^r) \cdot K_i^r - \sum_{i=1}^{M} (SBL+GC+X_i^p) \cdot X_i^p \cdot K_i^p + \frac{M_G \cdot (GC+SBL)}{RCL}}{\frac{M_G}{RCL} + \sum_{i=1}^{M} K_i^p \cdot (SBL+GC+X_i^p) + \sum_{i=1}^{N} K_i^r \cdot (SBL-X_i^r)} \tag{B.26}$$

Again, for all signs to be consistent, RCL must have the same sign as M_G; hence, M_G/RCL is always positive.

The displacements at the piston head front edge and at the stuffing box inside edge are,

$$\delta_f^p = (X^p + PHL) \cdot \theta \tag{B.27}$$

and

$$\delta_b^r = X^r \cdot \theta. \tag{B.28}$$

For a certain value of moment, if either δ_f^p is greater than PCL, or δ_b^r is greater than RCL, the next case with two kinematic constraints should be considered. If both the displacements are greater than the corresponding clearances, the proper case of two kinematic constraints to be used is determined by noting whether δ_f^p exceeds PCL first or δ_b^r exceeds RCL as θ is increased in Equations (B.27) and (B.28). If δ_f^p exceeds PCL, the case with kinematic constraints at the piston head front edge and at the stuffing box outside edge should be used, or if δ_b^r exceeds RCL, the case with kinematic constraints at both edges of the stuffing box should be considered.

Presence of Two Kinematic Constraints

Contact at Piston Head Edges

The metal-to-metal contact at the piston head edges with the cylinder wall (Figure 31) establishes that,

$$X^p = -PHL/2 \cdot 0 \tag{B.29}$$

and also,

$$\theta = 2 \cdot 0(PCL)/PHL \tag{B.30}$$

with the sign of the moment at the sliding connection.

Moments are summed about the piston head backside contact point,

$$F_f^p \cdot PHL + \sum_{i=1}^{M} F_i^p \cdot X_i^p + \sum_{i=1}^{N} F_i^r \cdot (GC + X_i^r) = M_G$$

from which

$$F_f^p = \frac{M_G - \sum_{i=1}^{M} F_i^p \cdot X_i^p - \sum_{i=1}^{N} F_i^r \cdot (GC + X_i^r)}{PHL} . \tag{B.31}$$

Summation of vertical forces gives the backside piston head edge contact point force,

$$F_b^p = F_f^p + \sum_{i=1}^{M} F_i^p - \sum_{i=1}^{N} F_i^r . \tag{B.32}$$

Contact at Stuffing Box Edges

The metal-to-metal contact at the stuffing box edges with the rod (Figure 32) establishes that,

$$X^p = GC + SBL/2 \cdot 0 \tag{B.33}$$

and also,

$$\theta = 2 \cdot 0(RCL)/SBL \tag{B.34}$$

with the sign of the moment at the sliding connection.

Moments are summed about the stuffing box inside edge contact point,

$$F_f^r \cdot SBL + \sum_{i=1}^{M} F_i^p \cdot (GC + X_i^p) + \sum_{i=1}^{N} F_i^r \cdot X_i^r = M_G$$

from which

$$F_f^r = \frac{M_G - \sum_{i=1}^{M} F_i^p \cdot (GC + X_i^p) - \sum_{i=1}^{N} F_i^r \cdot X_i^r}{SBL} . \tag{B.35}$$

The stuffing box inside contact point force is obtained from summation of vertical forces,

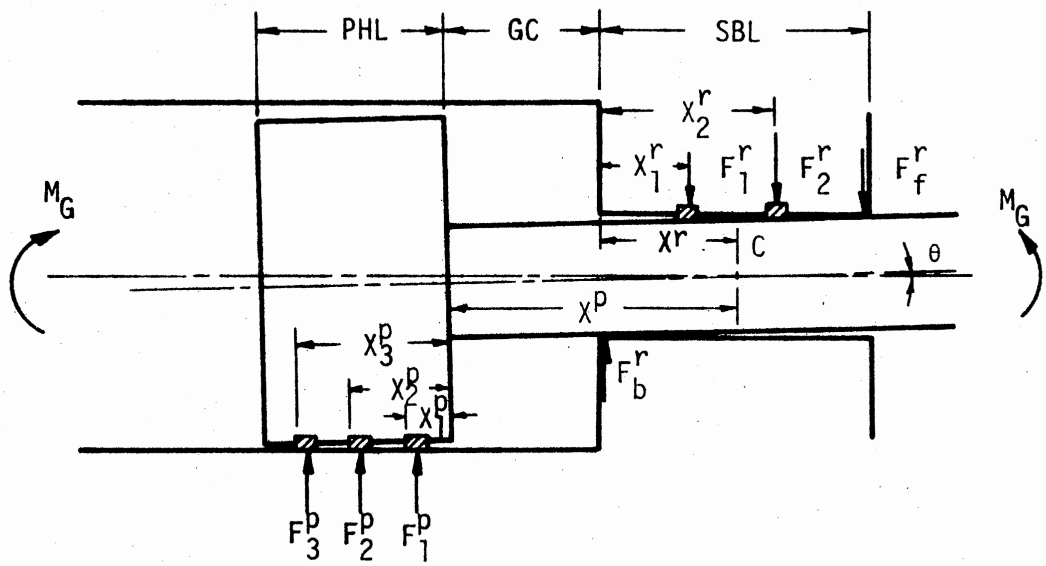

Figure 32. Contact at Stuffing Box Edges

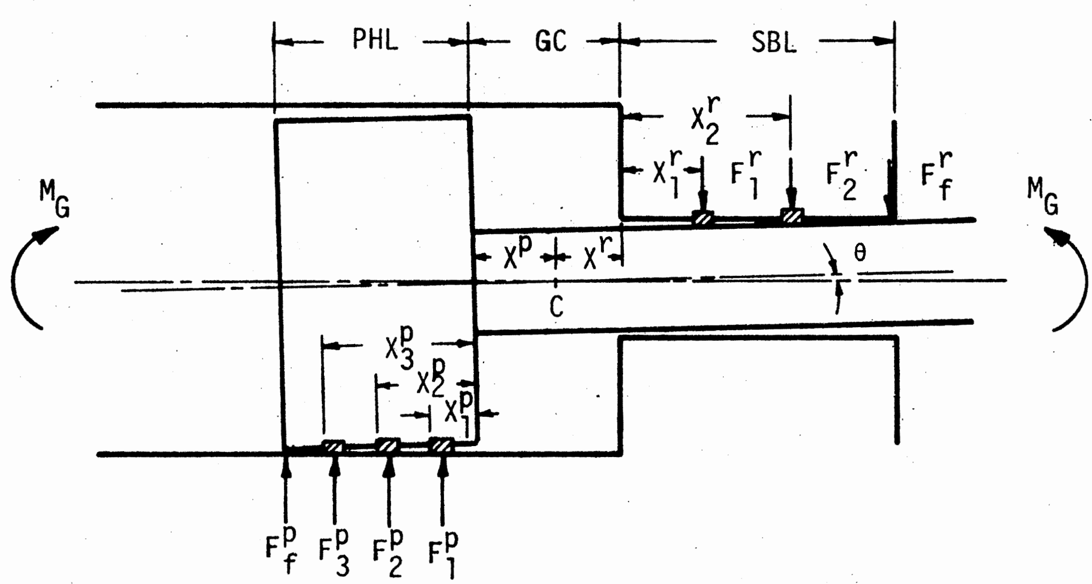

Figure 33. Contact at Piston Head Front and Stuffing Box Outside Edges

$$F_b^r = F_f^r + \sum_{i=1}^{N} F_i^r - \sum_{i=1}^{M} F_i^p. \tag{B.36}$$

Contact at Piston Head Front and

Stuffing Box Outside Edges

The metal-to-metal contact at the piston head front edge with the cylinder wall and the stuffing box outside edge with the rod (Figure 33) establishes that,

$$\theta = \frac{PCL + RCL}{PHL + GC + SBL} \tag{B.37}$$

with the sign of the moment at the sliding connection.

The distance of point C from the piston head backface is given by,

$$X^p = \frac{PCL}{\theta} - PHL \tag{B.38}$$

with PCL/θ being always positive for consistent sign convention.

Summation of moments about the stuffing box outside contact point gives,

$$F_f^p = \frac{M_G - \sum_{i=1}^{M} F_i^p \cdot (SBL + GC + X_i^p) + \sum_{i=1}^{N} F_i^r \cdot (SBL - X_i^r)}{PHL + GC + SBL} \tag{B.39}$$

Summation of vertical forces gives,

$$F_f^r = F_f^p + \sum_{i=1}^{M} F_i^p - \sum_{i=1}^{N} F_i^r. \tag{B.40}$$

Lateral Forces on Bearings and Seals

In all cases, after the crookedness angle, θ, is calculated, the lateral forces on the bearings and seals are calculated with Equation (B.3).

APPENDIX C

STRUCTURAL AND MATERIAL DETAILS OF CYLINDERS USED IN THE ANALYSIS

TABLE I

STRUCTURAL AND MATERIAL DETAILS OF OSU CYLINDER NO. 1

Identification: OSU No. 1			
No. Cyls. Tested: 1			
Dimensions (inches):			
Lengths:	Extended	105.69	
	Stroke	50.00	
	Cylinder	52.91	
	Rod	52.78	
Diameters:	Cylinder/outer	3.500	
	Cylinder/inner	3.020	
	Rod (solid)	2.000	
Clearances (each side):			
	Piston head/cylinder	0.003	
	Stuffing box/rod	0.026	
Seals and Bearings:			
Piston bearing:	Mat'l:	bronze	
	Thickness:	0.373 in.	
	Width:	0.530 in.	
	Modulus:	15000 ksi	
Piston seal:	Mat'l:	cotton fabric and neoprene green tweed compound No. 2410	
	Thickness:	0.318 in.	
	Width:	1.0 in.	
	Modulus:	400 ksi (assumed)	
Rod bearing:	Mat'l:	bronze	
	Thickness:	0.125 in.	
	Width:	1.00 in.	
	Modulus:	15000 ksi	
Rod seal:	None		

TABLE II

STRUCTURAL AND MATERIAL DETAILS OF OSU CYLINDER NO. 2

Identification:	OSU No. 2		
No. Cyls. Tested:	1		
Dimensions (inches):			
Lengths:	Extended	85.41	
	Stroke	40.00	
	Cylinder	42.88	
	Rod	43.72	
Diameters:	Cylinder/outer	4.000	
	Cylinder/inner	3.525	
	Rod (solid)	2.000	
Clearances (each side):			
	Piston head/cylinder	0.003	
	Stuffing box/rod	0.030	
Seals and Bearings:			
Piston bearings:	Mat'l:	bronze	
	Thickness:	0.382 in.	
	Width:	0.530 in.	
	Modulus:	15000 ksi	
Piston seal:	Mat'l:	Cotton fabric and neoprene green tweed compound No. 2410	
	Thickness:	0.382 in.	
	Width:	1.00 in.	
	Modulus:	400 ksi (assumed)	
Rod bearing:	Mat'l:	bronze	
	Thickness:	0.125 in.	
	Width:	1.00 in.	
	Modulus:	15000 ksi	
Rod seal:	None		

TABLE III

STRUCTURAL AND MATERIAL DETAILS OF OSU CYLINDER NO. 3

Identification: OSU No. 3

No. Cyls. Tested: 3

Dimensions (inches):

Lengths:	Extended	82.99
	Stroke	35.12
	Cylinder	38.65
	Rod	42.19

Diameters:	Cylinder/outer	4.500
	Cylinder/inner	4.000
	Rod (solid)	2.000

Clearances (each side):

Piston head/cylinder	0.014
Stuffing box/rod	0.006

Seals and Bearings:

Piston bearing:	Mat'l:	30-40% glass-filled nylon
	Thickness:	0.106 in.
	Width:	0.38 in.
	Modulus:	800 ksi (from data supplied by sponsor)
Piston seal:	Mfgr:	Goshen Rubber Co. and Dynamic Seal Co.
	Mat'l:	Fluorinated rubber with glass fibers
	Thickness:	0.198 in.
	Width:	0.278 in.
	Modulus:	250 ksi (assumed)
Rod bearing:	Mat'l:	Garlock polyurethane
	Thickness:	0.252 in.
	Width:	0.421 in.
	Modulus:	320 ksi (assumed)
Rod Seal:	Mat'l:	"Rulon"
	Thickness:	0.055 in.
	Width:	1.005 in.
	Modulus:	320 ksi (assumed)

TABLE IV

STRUCTURAL AND MATERIAL DETAILS OF OSU CYLINDER NO. 4

Identification: OSU No. 4

No. Cyls. Tested: 1

Dimensions (inches):

Lengths:	Extended	71.75
	Stroke	27.69
	Cylinder	33.13
	Rod	38.06
	Stop Tube	3
Diameters:	Cylinder/outer	6.0
	Cylinder/inner	5.270
	Rod (solid)	2.500

Clearances (each side):

Piston head/cylinder	0.057
Stuffing box/rod	0.015

Seals and Bearings:

Piston bearing:	Mat'l:	Phenolic nylatron
	Thickness:	0.191 in.
	Width:	1.5 in.
	Modulus:	850 ksi (from sponsor)
Piston seal:	Mat'l:	60% bronze-filled TFE
	Thickness:	0.250 in.
	Width:	0.375 in.
	Modulus:	197 ksi (from mfr.)
Rod bearing:	Mat'l:	Sintered iron
	Thickness:	0.320 in.
	Width:	2.2 in.
	Modulus:	200 ksi (assumed)
Rod seal:	Mat'l:	Parker compound N304-7
	Thickness:	0.3 in.
	Width:	0.5 in.
	Modulus:	190 ksi (assumed)

TABLE V

STRUCTURAL AND MATERIAL DETAILS OF OSU CYLINDER NO. 5

Identification: OSU No. 5

No. Cyls. Tested: 1

Dimensions (inches):

Lengths:	Extended	42.25
	Stroke	15.00
	Cylinder	19.26
	Rod	21.165

Diameters:	Cylinder/outer	4.500
	Cylinder/inner	4.002
	Rod (solid)	1.500

Clearances (each side):

Piston head/cylinder	0.012
Stuffing box/rod	0.004

Seals and Bearings:

Piston bearing:	Mat'l:	glass reinforced nylon
	Thickness:	0.122 in.
	Width:	0.510 in.
	Modulus:	900 ksi (assumed)
Piston seal:	Mat'l:	green tweed compound, Nylatron
	Thickness:	0.25 in.
	Width:	0.413 in.
	Modulus:	200 ksi (assumed)
Rod bearing:	Mat'l:	bronze
	Thickness:	0.128 in.
	Width:	1.703 in.
	Modulus:	1500 ksi
Rod seal:	Mat'l:	green tweed compound
	Thickness:	0.139 in.
	Width:	0.139 in.
	Modulus:	200 ksi (assumed)

TABLE VI

STRUCTURAL AND MATERIAL DETAILS OF OSU CYLINDER NO. 6

Identification: OSU No. 6			
No. Cyls. Tested: 1			
Dimensions (inches):			
Lengths:	Extended	40.50	
	Stroke	15.00	
	Cylinder	17.73	
	Rod	20.52	
Diameters:	Cylinder/outer	4.500	
	Cylinder/inner	4.002	
	Rod (solid)	1.250	
Clearances (each side):			
	Piston head/cylinder	0.004	
	Stuffing box/rod	0.002	
Seals and Bearings:			
Piston bearing:		Mat'l:	leather
		Thickness:	0.188 in.
		Width:	0.095 in.
		Modulus:	200 ksi (assumed)
Piston seal:		Mat'l:	synthetic rubber
		Thickness:	0.21 in.
		Width:	0.21 in.
		Modulus:	800 ksi
Rod bearing:		Mat'l:	bronze
		Thickness:	0.121 in.
		Width:	1.238 in.
		Modulus:	15000 ksi
Rod Seals:	No. 1	Mat'l:	synthetic rubber
		Thickness:	0.139 in.
		Width:	0.139 in.
		Modulus:	800 ksi
	No. 2	Mat'l:	polyurethane
		Thickness:	0.139 in.
		Width:	0.109 in.
		Modulus:	200 ksi (assumed)

TABLE VII

STRUCTURAL AND MATERIAL DETAILS OF OSU CYLINDER NO. 7

Identification: OSU No. 7

No. Cyls. Tested: 1

Dimensions (inches):

Lengths:	Extended	34.415	
	Stroke	12.000	
	Cylinder	13.295	
	Rod	18.020	
Diameters:	Cylinder/outer	3.455	
	Cylinder/inner	2.9985	
	Rod (solid)	1.499	

Clearances (each side):

Piston head/cylinder	-0.01325 in.
Stuffing box/rod	-0.00150 in.

Seals and Bearings:

Piston bearing:	Mat'l:	unknown
	Thickness:	0.127 in.
	Width:	0.492 in.
	Modulus:	600 ksi (assumed)
Piston seal:	Mat'l:	TFE (glass filled)
	Thickness:	0.063 in.
	Width:	0.210 in.
	Modulus:	230 ksi (assumed)
Rod bearing:	None	
Rod seal:	Mat'l:	Polypack
	Thickness:	0.189 in.
	Width:	0.421 in.
	Modulus:	600 ksi (assumed)

TABLE VIII

STRUCTURAL AND MATERIAL DETAILS OF OSU CYLINDER NO. 8

Identification: OSU No. 8

No. Cyls. Tested: 2

Dimensions (inches):

Lengths:	Extended	26.625
	Stroke	9.000
	Cylinder	10.400
	Rod	12.787

Diameters:	Cylinder/outer	2.000
	Cylinder/inner	1.750
	Rod (solid)	0.747

Clearances (each side):

Piston head/cylinder	-0.0025 in.
Stuffing box/rod	-0.0025 in.

Seals and Bearings:

Piston bearing:	Mat'l:	Teflon
	Thickness:	0.055 in.
	Width:	0.088 in.
	Modulus:	600 ksi
Rod bearing:	Mat'l:	Teflon
	Thickness:	0.125 in.
	Width:	0.213 in.
	Modulus:	600 ksi
Piston seal:	None	
Rod seal:	None	

APPENDIX D

COMPUTER PROGRAM FOR HYDRAULIC CYLINDERS--SACFI

```
      IMPLICIT REAL * 8 ( A-H, O-Z )
C---- >>> DRIVER FOR PROGRAM SACFI
C---- >>> DIMENSIONS OF A & B DEPEND ON VALUE OF MWIDE
      DIMENSION A( 64, 8), B( 64 ),  CD( 64), BD( 64), AD(64 , 8 )
C---- >>> DIMENSIONS OF FOLLOWING ARRAYS DEPEND  ON VALUE OF NPMAX
      DIMENSION X( 8), FXY( 8 ),FXZ( 8), NPCODE( 8), DEXY(8), DEXZ( 8),
     1          ECXY( 8 ), ECXZ( 8), BMXZ( 8), BMXY( 8 ),SHXY( 8),
     2           SHXZ( 8) , AXMULT( 8 ), APMOY( 8 ), APMOZ( 8 ),PI( 8 )
C---- >>> MAXIMUM NO OF NODES
               NPMAX    = 8
C---- >>> NUMBER OF ELEMENTS
               NELMAX   = NPMAX - 1
C---- >>> MAX STORAGE SIZE
               MWIDE    = 8
               MLONG    = 64
               MLONG1   = MLONG / 2
      CALL SACFI
     I          ( A, B, AD, BD, CD, X, FXY, FXZ, NPCODE, DEXY, DEXZ,
     I            ECXY, ECXZ, BMXZ, BMXY, SHXY, SHXZ,
     I            NPMAX, NELMAX, MWIDE, MLONG, MLONG1, AXMULT, APMOY,
     I            APMOZ, PI                                           )
      STOP
      END
```

```
      SUBROUTINE SACFI
     I          ( A, B, AD, BD, CD, X, FXY, FXZ, NPCODE, DEXY, DEXZ,
     I            ECXY, ECXZ, BMXZ, BMXY, SHXY, SHXZ,
     I            NPMAX, NELMAX, MWIDE, MLONG, MLONG1, AXMULT, APMOY,
     I            APMOZ, PI                                           )
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / BRGSTF / PRKX, SPRK, RBKY, SRBK
      COMMON / CLEAR  / PCL, RCL
      COMMON / CLERNC / CSBC, PCL1, RCL1
      COMMON / CRPROP / RDZ, CYZ, RDZI, CYZI, HSCCI, HSCCO, HSCRI,
     *                  HSCRO, BAREAC, BAREAR, CAREAC, CAREAR
      COMMON / DIAMTS / COD, CID, ROD, RID, CPD, RPD, PHD, SBD
      COMMON / FRCONS / FCCY, FCRD
      COMMON / FSOPTF / OPPRE, ALTH, ALF, FS, LFSTP
      COMMON / GLDFOR / FX(5), FY(5), F1, F2, F3, F4
      COMMON / ID     / IDCARD(40), NPROB, IPROB(19), LPRTP
      COMMON / INCLFR / CINCL, FCC, FCR
      COMMON / LENGTS / STROK, PHL, SBL, EPTK, CHDS, LFLUID
      COMMON / PISTON / PRW(5), PRT(5), PRE(5), PRK(5), PRDST(5), NPHBR
      COMMON / PROPTS / ECYL, EROD, FYCYL, FYROD
      COMMON / RODBRS / RBW(5), RBT(5), RBE(5), RBK(5), RBDST(5), NRDBR
      COMMON / STPTBS / CL, RL, STPTB
      COMMON / UNITS  / LNTU, LODU, LPREU, LANGU
      COMMON / WGTCON / WPH, WSB
      COMMON / WGTVER / WC, WR
      COMMON / ELEN   / NUMEL,NUMNP, NOCYE, NGL, NGLA
      COMMON /  ORD1  / NODE1( 10), XCRD1( 10), NODE2( 10), XORD2(10)
      COMMON /  TEMP  / NODCY( 10), LCEXY( 10), LCEXZ( 10), ECXYA( 10 ),
     *                 ECXZA( 10), KODEXY( 10), KODEXZ( 10), APMOY1(10),
     *                 APMOZ1( 10 )
      DATA ZERO  , ONE, H180 / 0.00D00,1.00D00, 180.00D00 /
      DATA PI / 3.14159265D00 /
      DATA IBLNK, LOAD, LDEG / 4H    , 4HLOAD, 4HDEG /
      DATA HUNDRD / 100.00D00 /
      DIMENSION X( NPMAX ), NPCODE ( NPMAX), FXY( NPMAX ), FXZ( NPMAX ),
     1          DEXY( NPMAX), DEXZ( NPMAX ), A( MLONG, MWIDE ),
     2             B( MLONG ), ECXY( NPMAX ), ECXZ( NPMAX ),
     3            CD( MLONG ), GLFORC( 8 ), BMXZ( NPMAX ),
     4            BMXY( NPMAX), SHXY( NPMAX ), SHXZ( NPMAX )
      DIMENSION AD( MLONG, MWIDE ) , BD( MLONG ), AXMULT( NPMAX ),
     1          APMOY( NPMAX ), APMOZ( NPMAX ), PI ( NPMAX )
                NPROB    = IBLNK
                MBAND    = 8
  100 CALL INECHO
     I          ( IBLNK, GC, NPMAX ,
     C            IFLAG1, IFLAG2, NCYL, NROD, NCOND  , EXL, AXMULT      )
                FYCYLT   = FYCYL
                FYRODT   = FYROD
      CALL DIST
     I          ( NCYL, NROD, NCOND, IFLAG1, IFLAG2, NPMAX, NELMAX,
     I          MLONG, MWIDE, GC, EXL ,LPRTP, RPD,
     O          X, NPCODE , ECXY, ECXZ, APMOY ,APMOZ                    )
      CALL CONST
     I          ( ECYL, EROD, CHDS, LANGU,
     C            CYI , RDI, CYK, RDK                                   )
      CALL TRIALP
     I          ( EROD, LPRTP, RDI, FYCYL, BAREAC, HSCCI, FYROD,
     I            BAREAR, HSCRI , EXL , AXMULT, NPMAX ,NUMNP,
```

```
     0          PINCR1, PINCR2, P                                          )
                FILOAD  = P
C--- >>> SET UP KEYS
C
C--- >>> KEYT & KEYP ARE KEYS FOR PROPER LOAD INCREMENT
C---- >>> KEYST IS SET TO CHECK INPUT PR AGAINST CRITICAL PRESS
C---- >>> KEYF IS SET TO QUIT LOOP AT FINAL ITERATION
  200           KEYF    = 1
                KEYST   = 1
                KEYT    = 1
                KWIT    = 1
                KEYP    = 1
                INDEX   = 1
                KTERAT  = 1
                RHOC    = ZERO
                BETA    = ZERO
                TETAY   = ZERO
                KITER   = 1
  300 CALL EQSTIF
     I          ( P, MWIDE, MLONG, X, CYI, RDI, EXL, NPMAX, NELMAX,NPCODE
     I           ,ECXY, ECXZ, MBAND, RHOC, BETA,KITER,AXMULT,APMOY,APMOZ,
     C           A , B, PI                                                 )
      DO 350 IZ = 1 , MLONG
                BD( IZ )= B( IZ )
      DO 350 JZ = 1 , MWIDE
            AD( IZ, JZ )= A( IZ , JZ )
  350 CONTINUE
  400 CALL BANSOL ( BD, AD, MBAND, MWIDE, MLONG , CD , MLONG1              )
  500 CALL GLAFOR
     I           ( X, CYI, RDI, CD, NPMAX, PI,MLONG,B,RHOC,BETA,KITER,
     I             FILOAD, P,
     C            GLFORC, BMG, GAMA                                        )
  600 CALL THETA
     I          ( PRK, PRDST, RBK, RBDST, NPHBR, NRDBR,
     I            GC, BMG, PHL, SBL,
     0           XGL, YGL, TETAF                                           )
         IF( LPRTP . NE. 3 ) GO TO 650
         IF( KEYST.EQ.1 ) GO TO 650
                ALTH1   = ALTH
                TEMP2   = PI / H180
         IF( LANGU. EQ. LDEG ) ALTH1 = ALTH * TEMP2
                KTERAT  = 1
      CALL STOP1B
     I          ( TETAF, NPHBR, NRDBR, ALTH, ALF, STROK, KTERAT, GC        )
                EXL      = CL + EPTK + CHOS + RL - GC
      CALL DIST
     I          ( NCYL, NPOD, NCOND, IFLAG1, IFLAG2, NPMAX, NELMAX,
     I          MLONG, MWIDE, GC, EXL ,LPRTP, RPD,
     0          X, NPCODE , ECXY, ECXZ, APMOY ,APMOZ                       )
                KITER   = 1
  650       X ( NGL )   = X( NOCYE ) + PHL + XGL
                RHOC    = TETAF * DSIN( GAMA )
                BETA    = TETAF * DCOS ( GAMA )
              DTETA     = DABS( TETAY / HUNDRD )
                DIFF = DABS ( TETAF - TETAY  )
                TETAY   = TETAF
                KITER   = 2
         IF( KTERAT. NE. 1 ) GO TO 300
         IF ( DIFF . LT. DTETA ) GO TO 800
         IF( INDEX. GT. 25 ) GO TO 700
                INDEX   = INDEX + 1
         GO TO 300
  700           PRINT 2000
  800 CONTINUE
                KITER   = 1
      CALL FORCES
     I          ( X, CYI, RDI, CD, NPMAX, MLONG,PI, RHOC, BETA,
     C            BMXY, SHXY, BMXZ, SHXZ, AMAXCY, NODEC,
     0            AMAXPD, NODER, DEXY, DEXZ                                )
      CALL MAXMOM
     I          ( NODEC, NODER, CYI, RDI, X,PI, BMXY, CD, MLONG,
     I            SHXY, BMXZ, SHXZ, NPMAX, DEXY, DEXZ, RHOC, BETA,
     0            AMAXCY, AMAXRD, XCM, XRM, DEFLC, DEFLR, PC, PR  .        )
  910 CALL STRESS
     I          ( KEYF, KEYT, KEYP, RID, CHDS, OPPRE,  FYROD , FYCYL ,
     *            PINCR1, PINCR2, KEYST, LFLUID, P, AMAXCY, AMAXRD,PI,PC,
     *            PR,
     C            HSC, HSR, AXTEN, CSTR, RSTR, CSS, NCSS, NPMAX,
     *           RSS, NRSS                                                 )
                INDEX   = 1
         IF ( KEYF . NE . 3 ) GO TO 300
         IF ( KEYST . NE. 1 ) GO TO 900
         IF ( LPRTP . EQ . 1 ) GO TO 900
                PRES    = P / BAREAC
         IF ( OPPRE . GT . PRES ) GO TO 2020
                P = OPPRE * BAREAC
                KEYST   = 2
                TETAY   = ZERO
         GO TO 300
  900 CALL OUTPUT
     I          ( KWIT, BAREAC, XCM, XRM, DEFLC, DEFLR , CHDS,GC, TETAY,
     I            FYCYLT, FYRODT, CSTR, RSTR, HSC, HSR,
     I            AXTEN, NPHBR, NRDBR, TETAY, CSS, NCSS, RSS, NRSS,P,EXL)
         IF ( KWIT . NE. 1 ) GO TO 200
         IF ( LPRTP . NE. 1 ) GO TO 100
         IF ( FS . LE. ONE ) GO TO 100
                P        = P / FS
                KWIT    = 2
C
C  >>>>> APPLY FACTOR OF SAFTEY
C
         IF ( LFSTP . EQ. LOAD ) GO TO 300
                FYCYLT  = FYCYL / FS
                FYRODT  = FYROD / FS
          GO TO 200
 2020 PRINT 2050, PRES
        GO TO 100
 2000 FORMAT( 15X, ' CROOKEDNESS ANGLE NOT CONVERGING '                    )
 2050 FORMAT ( 1H1, 20(/),10(10X,21H*** *** ERROR *** ***  / ),////,
     1          10X, 38HOPERATING PRESSURE IS GREATER THAN THE      /
     2          10X, 42HCAPACITY( CRITICAL LOAD ) OF THE CYLINDER.  //
     3          10X, 37HTHE MAXIMUM PRESSURE FOR THE CYL IS =,1PD10.3,//)
 2100 CONTINUE
      STOP
      END
```

```
      SUBROUTINE INECHO
     I          ( IBLNK, GC, NPMAX ,
     C            IFLAG1, IFLAG2, NCYL, NROD, NCCND  , EXL, AXMULT      )
C
C---- >>> SUBROUTINE TO READ AND ECHO INPUT DATA FOR SACREG
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / CLERNC / CSBC, PCL1, RCL1
      COMMON / DIAMTS / CCD, CID, ROD, RID, CPD, RPD, PHD, SBD
      COMMON / FSOPTF / OPPRE, ALTF, ALF, FS, LFSTP
      COMMON / ID     / ICCARD(40), NPROB, IPROB(19), LPRTP
      COMMON / INCLFR / CINCL, FCC, FCR
      COMMON / LENGTS / STROK, PHL, SBL, EPTK, CHDS, LFLUID
      COMMON / PISTCN / PRW(5), PRT(5), PRE(5), PRK(5), PROST(5), NPHBR
      COMMON / PROPTS / ECYL, EROD, FYCYL, FYROD
      COMMON / RODBRS / RBW(5), RBT(5), RBE(5), RBK(5), RBOST(5), NRDBR
      COMMON / STPTBS / CL, RL, STPTB
      COMMON / UNITS  / LNTU, LODU, LPREU, LANGU
      COMMON / WGTINI / WC1, WR1, WPH1, WSB1
      COMMON /  ORD1  / NODE1( 10), XCRD1( 10), NODE2( 10), XCRD2(10)
      COMMON /  TEMP  / NODCY( 10), LCEXY( 10), LCEXZ( 10), ECXYA( 10 ),
     *                  ECXZA( 10), KODEXY( 10), KODEXZ( 10), APMOY1(10),
     *                  APMOZ1( 10 )
C
      DIMENSION PRK1(5), RBK1(5),AXMULT( NPMAX )
C
      DATA NCONS / 4HCONS /
      DATA ZERO, TWO / 0.0D00, 2.0D00 /
      DATA ISELF / 4HSELF/
      DATA ONE / 1.0D000 /
      DATA LPIN, LFIX / 3HPIN, 3HFIX /
      DATA KEEP, IEND, LYES / 4HKEEP, 3HEND, 3HYES /
C
C---- >>> FORMATS
C
   10 FORMAT ( 20A4                                                     )
   20 FORMAT ( A4, 19A4                                                 )
   30 FORMAT ( 4X, I1, 5X, 7( A4, 6X )                                  )
   40 FORMAT ( 4X, 4( 6X, A4 )                                          )
   50 FORMAT ( 8F10.0                                                   )
   60 FORMAT ( 5F10.0, 10X, A3                                          )
   80 FORMAT ( 6X, A4, 2I10 , 6X, A4                                    )
   70 FORMAT ( 7F10.3, 6X, A4                                           )
   85 FORMAT( 8F10.3  )
   90 FORMAT ( I10, F10.3, I10, F10.3, 7X, A3                           )
  100 FORMAT( I10, 7X, A3, 7X, A3, 4F10.3,7X,A3                         )
  140 FORMAT ( 1H1,5X,32HPROGRAM SACFI - STRESS ANALYSIS ,
     1         23HOF HYDRAULIC CYLINDERS,//2 (5X, 20A4, / ),/           )
  150 FORMAT ( 5X, 8HPROBLEM , A4, //, 1X, 19A4                         )
  160 FORMAT ( /, 5X, 11HINPUT DATA:, //, 5X, 8HTABLE 1:, 5X,
     1         12HCONTROL DATA                                          )
  170 FORMAT ( /, 10X, 41HPROBLEM TYPE = 1 - CRITICAL LOAD ANALYSIS,
     1         31H & ANALYSIS FOR A FACTORED LOAD, /                    )
  180 FORMAT ( /, 10X, 27HPROBLEM TYPE = 2 - ANALYSIS,
     1         26H FOR A PARTICULAR PRESSURE, /                         )
  190 FORMAT ( /, 10X, 27HPROBLEM TYPE = 3 - ANALYSIS,
     1         39H TO DETERMINE SUITABLE STOP-TUBE LENGTH, /            )
  210 FORMAT ( /, 18X, 37HTABLES RETAINED FROM PREVIOUS PROBLEM, //,
     1         20X, 2H 2, 4X, 2H 3, 4X, 2H 4, 4X, 2H 5, 4X, 2H 6,
     2         4X, 2H 7, /, 17X, 6( 2X, A4 )                            )
  240 FORMAT ( 23X, 25HNO KEEP OPTIONS EXERCISED, /                     )
  260 FORMAT ( /, 5X, 33HTABLE 2:     UNITS OF MEASUREMENT,//, 17X,
     1         6HLENGTH, 6X, 4HLOAD, 5X, 8HPRESSURE, 3X, 7HANGULAR,
     2         //, 11X, 4( 7X, A4 )                                     )
  270 FORMAT ( //, 5X, 32HTABLE 3:     CYLINDER DIMENSIONS, //, 10X,
     1         8HLENGTHS:, //, 19X, 23HSTROKE      PISTON HEAD, 2X,
     2         40HSTUFFING BOX    END PLATE    HINGE DIST., //, 14X,
     3         5( 2X, 1PD12.5 )                                         )
  280 FORMAT ( //, 18X, 20HCYLINDER            ROD, 8X,
     1         23HEXTENDED      STOP TUBE                               )
  290 FORMAT ( /, 14X, 4( 2X, 1PD12.5 )                                 )
  300 FORMAT ( /, 15X, 23HTHESE NOT INPUT BECAUSE,
     1         35H STOP TUBE LENGTH ANALYSIS IS ASKED, /                )
  310 FORMAT ( /, 10X, 10HDIAMETERS:, //, 17X, 10HCYL. OUTER, 4X,
     1         38HCYL. INNER      ROD OUTER      ROD INNER, /           )
  320 FORMAT (    14X, 4( 2X, 1PD12.5 ), 2X, 5HSOLID ROD, /             )
  330 FORMAT (    14X, 4( 2X, 1PD12.5 ), 2X, 10HHOLLOW ROD              )
  335 FORMAT (    72X, 10HWITH FLUID                                    )
  340 FORMAT (    72X, 13HWITH NO FLUID                                 )
  350 FORMAT ( /, 18X, 23HCYL. PIN *    ROD PIN *, 3X,
     1         26HPISTON HEAD @  STUF. BOX @,//, 14X, 4( 2X, 1PD12.5 ),
     2         /, 16X, 26H(* ZERO, THE END IS FIXED),
     3         32H (@ ZERO, OTHER OPTION IS INPUT)                      )
  360 FORMAT (1H1,10X, 19HCLEARANCES BETWEEN:, //, 12X,
     1         2( 6X, 8HCYLINDER ), 8X, 3HROD, /, 9X, 3( 11X, 3HAND ),
     2         /, 16X, 12HSTUFFING BOX, 2X, 13HPISTON HEAD @, 2X,
     3         11HSTUF. BOX @,  //, 14X, 3( 2X, 1PD12.5 ), /, 29X,
     4         31H(@ ZERO, OTHER OPTION IS INPUT)                       )
  370 FORMAT (     /4X, 31HTABLE 4:     BEARINGS AND SEALS, //, 10X,
     1         16HPISTON BEARINGS:, /                                   )
  380 FORMAT (     21X, 3( 2H A, 12X ), 2H B, 7X, 13HDISTANCE FROM, /,
     1         20X, 5HWIDTH, 7X, 9HTHICKNESS, 2X, 14HYOUNGS MODULUS, 3X,
     2         9HSTIFFNESS, 5X, 9HBACK FACE, //,
     3         5( 14X, 5( 2X, 1PD12.5 ), / )                            )
  390 FORMAT (     10X, 13HROD BEARINGS:, /                             )
  400 FORMAT (     15X, 48H(A IS USED TO CALCULATE B - HENCE, EITHER A OR
     1         , 10HB IS INPUT, /, 28X,
     2         46HZERO'S ABOVE INDICATE THAT THEY ARE NOT INPUT), /     )
  410 FORMAT ( /, 5X, 44HTABLE 5:     WEIGHTS AND MATERIAL PROPERTIES,
     1         //, 10X, 17HWEIGHTS OF PARTS:, //, 18X, 8HCYLINDER, 9X,
     2         3HROD, 7X, 11HPISTON HEAD, 2X, 12HSTUFFING BOX, /, 21X,
     3         17H(PER UNIT LENGTH), //, 14X, 4( 2X, 1PD12.5 ), /       )
  420 FORMAT ( /, 10X, 20HMATERIAL PROPERTIES:, //, 22X,
     1         14HYOUNGS MODULUS, 15X, 12HYIELD STRESS, /, 10X,
     2         2( 8X, 8HCYLINDER, 9X, 3HROD ),//, 14X, 4( 2X, 1PD12.5)/)
  430 FORMAT ( //5X, 41HTABLE6: INCLINATION,FRICTION COEFFICIENT,
     1         17HFACTOR OF SAFETY,/10X,
     2         20HCYLINDER INCLINATION,5X, 1PD10.3                      )
  440 FORMAT ( 10X,21HFRICTION COEFFICIENTS,/18X,
     1         12HCYLINDER END, 5X, 1PD10.3,/23X,
     3         7HROD END, 5X, 1PD10.3                                   )
  450 FORMAT(1H1,5X,20HTABLE7: STATION DATA,/12X,
     2         A4, 6HOPTION,//12X,
     1         18HNUMBER OF ELEMENTS,/22X,
     2         8HCYLINDER, 5X, I4, /27X,
     3         3HROD,5X, I4                                             )
```

```
460 FORMAT(/5X,37HSTA   X-COORD    STA    X-COORD  NSEG ,/    , 10(
   1          I8,2X,1PD10.3,I4,1X,1PD10.3,/  )                          )
475 FORMAT( //5X,38HTABLE8: FIXITY CONDITIONS,ECCENTRICITY ,
   1          11H OF LOADING,/5X,
   2          45HNODE   FIXITY ALONG PLANE  ECCENTRICITY ALONG,11X,
   3          13HMOMENTS ABOUT, /14X,
   3          35HXY        XZ          XY          XZ,13X,
   5         11HY          Z                                            )
480 FORMAT(//5X, 10(I4,5X,A3,6X,A3,7X,1PD10.3,2X,1PD10.3,2X,
   1          1PD10.3,2X,1PD10.3, /5X )                                 )
490 FORMAT( //5X, 34HAXIAL LOAD DISTRIBUTION IS UNIFORM                 )
494 FORMAT( //20X,32HAXIAL LOAD MAGNIFICATION FACTORS,/25X,
   *         7HNODE NO,5X,24HAXIAL LOAD MAGNIFICATION                   )
495 FORMAT( /10X, I20, 12X, F10.3                                       )
500 FORMAT ( /, 10X, 27HONLY CRITICAL LOAD ANALYSIS , /                 )
510 FORMAT ( /, 10X, 19HFACTOR OF SAFETY = , F6.3, 4H ON , A4, /        )
520 FORMAT ( /, 10X, 21HOPERATING PRESSURE = , 1PD12.5, /               )
530 FORMAT ( /, 10X, 32HOPERATING CYLINDER PRESSURE   = , 1PD12.5,//,
   1          10X, 32HALLOWABLE CROOKEDNESS ANGLE   = , 1PD12.5,
   2          10H  AT GLAND, //,10X,32HALLOWABLE TOTAL LATERAL FORCE =
   3          1PD12.5, 13H  ON BEARINGS, /                              )
550 FORMAT ( ///, 10X, 30H*****  ERROR IN LENGTHS  *****, /             )
560 FORMAT ( ///, 10X, 7H*****  ,
   1          32HERROR : PHD IS GREATER THAN CID , 6H *****, /          )
570 FORMAT ( ///, 10X, 7H*****  ,
   1          37HERROR : RD IS GREATER THAN SBD  *****, /               )
580 FORMAT ( //, 10X, 6H***** , 19HPROGRAM TERMINATED , 5H*****         )
590 FORMAT ( 1H1                                                        )
       IF ( NPROB .NE. IBLNK ) GO TO 650
C
C---- >>> READ AND ECHO RUN AND PROBLEM IDENTIFICATION
C
      READ ( 5, 10 ) ( IDCARD( I ), I = 1, 40 )
  650 READ ( 5, 20 ) NPROB, ( IPROB( I ), I = 1, 19 )
C
C---- >>> TEST FOR END OF RUN
C
       IF ( NPROB .EQ. IBLNK ) GO TO 1700
      PRINT140, ( IDCARD( I ), I = 1, 40 )
      PRINT 150, NPROB, ( IPROB( I ), I = 1, 19 )
C
C---- >>> READ TABLE 1:  PROBLEM TYPE AND TABLES TO BE RETAINED FROM
C                        PREVIOUS PROBLEM
C
      READ ( 5, 30 ) LPRTP, KEEP2, KEEP3, KEEP4, KEEP5, KEEP6, KEEP7,
     1               KEEP8
       IF ( KEEP2 .EQ. KEEP ) GO TO 660
C
C---- >>> READ TABLE 2:  UNITS OF MEASUREMENT
C
      READ ( 5, 40 ) LNTU, LODU, LPREU, LANGU
  660  IF ( KEEP3 .EQ. KEEP ) GO TO 690
      READ ( 5, 60 ) STROK, PHL, SBL, EPTK, CHDS, LFLUID
       IF ( LPRTP .EQ. 3 ) GO TO 670
C
C---- >>> READ TABLE 3:  LENGTHS AND DIAMETERS
C
      READ ( 5, 50 ) CL, RL, EXL, STPTB
  670 READ ( 5, 50 ) COD, CID, ROD, RID, CPD, RPD, PHC, SBD
      READ ( 5, 50 ) CSBC, PCL1, RCL1
C
C---- >>> CALCULATE GLAND CLEARANCE
C
            GC      = ZERO
       IF ( LPRTP .NE. 3 ) GC = CL - STROK - PHL
C
C---- >>> TEST FOR PROPER INPUT
C
       IF ( LPRTP .EQ. 3 ) GO TO 680
            A       = EXL - CHDS - EPTK - CL - SBL - RPD / TWO
       IF ( A .LT. STROK ) GO TO 1000
  680  IF ( PCL1 .GT. ZERO .OR. RCL1 .GT. ZERO ) GO TO 690
       IF ( PHD .GT. CID ) GO TO 1100
       IF ( ROD .GT. SBD ) GO TO 1200
C
  690  IF ( KEEP4 .EQ. KEEP ) GO TO 735
C
C---- >>> READ TABLE 4:  PISTON RINGS AND ROD BEARINGS DETAILS
C
            I = 1
            J = 1
  700 READ ( 5, 60 ) PRW(I), PRT(I), PRE(I), PRK1(I), PRDST(I), NEND
            PRK(I) = PRK1(I)
       IF ( NEND .EQ. IEND ) GO TO 710
            I = I + 1
       GO TO 700
  710       NPHBR  = I
  720 READ ( 5, 60 ) RBW(J), RBT(J), RBE(J), RBK1(J), RBDST(J), NEND
            RBK(J) = RBK1(J)
       IF ( NEND .EQ. IEND ) GO TO 730
            J = J + 1
       GO TO 720
  730       NRDBR  = J
  735  IF ( KEEP5 .EQ. KEEP ) GO TO 740
C---- >>> READ TABLE 5:  WEIGHTS OF PARTS AND MATERIAL PROPERTIES
      READ ( 5, 50 ) WC1, WR1, WPH1, WSB1, ECYL, EROD, FYCYL, FYROD
  740  IF ( KEEP6 .EQ. KEEP ) GO TO 750
C---- >>> READ TABLE 6: INCLINATION,FRICTION COEFFICIENT,
C        FACTOR OF SAFTEY, ALLOWABLE CROOKEDNESS ANGLE & DEFLN
      READ ( 5, 70 ) CINCL, FCC, FCR, FS, OPPRE, ALTH, ALF, LFSTP
  750  IF ( KEEP7 . EQ . KEEP ) GO TO 775
C
C---- >>> READ TABLE 7 STATION DATA
C
            I = 1
            IFLAG1  = I
      READ ( 5 , 80 ) NCOND , NCYL, NROD, NAXCON
            NUMNP   = NCYL + NROD + 1
      IF ( NCOND . EQ. ISELF ) GO TO 760
      GO TO 768
  760 READ ( 5, 90 ) NODE1( I ), XCRD1( I ) , NODE2( I ),XCRD2( I ), NEND
       IF ( NEND . EQ. IEND ) GO TO 765
            I = I + 1
      GO TO 760
  765       IFLAG1  = I
  768 IF( NAXCON . EQ . NCONS ) GO TO 770
```

```
      READ ( 5 , 85 ) ( AXMULT( IMR ), IMR = 1 , NUMNP   )
         GO TO 775
  770 DO 771 IND = 1 , NUMNP
            AXMULT( IND ) = ONE
  771 CONTINUE
C
C--- >>> READ TABLE 8, FIXITY CONDITICNS,ECCENTRICITY OF LOADING
  775     IF ( KEEP8 . EQ . KEEP ) GO TO 786
                J        = 1
  780 READ ( 5, 100) NCDCY( J ) ,LCEXY( J ), LCEXZ( J), ECXYA( J),
     *                 ECXZA( J ),   APMCY1( J ),APMCZ1( J ), IENDN
          IF ( LCEXY ( J ) . EQ. LPIN ) KODEXY( J ) = 1
          IF ( LCEXY ( J ) . EQ. LFIX ) KODEXY( J ) = 2
          IF ( LCEXZ ( J ) . EQ. LPIN ) KODEXZ( J ) = 1
          IF ( LCEXZ ( J ) . EQ. LFIX ) KODEXZ( J ) = 2
          IF ( LCEXY ( J ) . EQ. IBLNK) KODEXY( J ) = 0
          IF ( LCEXZ ( J ) . EQ. IBLNK) KODEXZ( J ) = 0
          IF ( IENDN . EQ. IEND ) GO TO 785
                J        = J + 1
          GO TO 780
C
C---- >>> PRINT ALL THE TABLES READ
C
  785           IFLAG2  = J
  786 PRINT 160
          IF ( LPRTP - 2 ) 790, 800 , 810
  790 PRINT 170
      GO TO 820
  800 PRINT 180
      GO TO 820
  810 PRINT 190
  820 PRINT 210, KEEP2, KEEP3, KEEP4, KEEP5, KEEP6, KEEP7, KEEP8
          IF ( KEEP2 .NE. IBLNK ) GO TO 830
          IF ( KEEP3 .NE. IBLNK ) GO TO 830
          IF ( KEEP4 .NE. IBLNK ) GO TO 830
          IF ( KEEP5 .NE. IBLNK ) GO TO 830
          IF ( KEEP6 .NE. IBLNK ) GO TO 830
          IF ( KEEP7 .EQ. IBLNK ) PRINT 240
  830 CONTINUE
      PRINT 260, LNTU, LODU, LPREU, LANGU
      PRINT 270, STRCK, PHL, SBL, EPTK, CHDS
      PRINT 280
          IF ( LPRTP .EQ. 3 ) GO TO 850
      PRINT 290, CL, RL, EXL, STPTB
          GO TO 860
  850 PRINT 300
  860 PRINT 310
          IF ( RID .GT. ZERO ) GO TO 880
      PRINT 320, COD, CID, ROD, RID
          GO TO 890
  880 PRINT 330, COD, CID, ROD, RID
          IF ( LFLUID .NE. LYES ) GO TO 885
      PRINT 335
          GO TO 890
  885 PRINT 340
  890 PRINT 350, CPD, RPD, PHD, SBD
      PRINT 360, CSBC, PCL1, RCL1
      PRINT 370
      PRINT 380, ( PRW(I), PRT(I), PRE(I), PCK1(I),PPCST(I),I=1, NPROR )
      PRINT 390
      PRINT 380, ( RBW(I), RBT(I), RBE(I), RPK1(I),RBDST(I),I=1, NROBR )
      PRINT 400
      PRINT 410, WC1, WP1, WPH1, WSB1
      PRINT 420, ECYL, EROD, FYCYL, FYROD
      PRINT 430 , CINCL
      PRINT 440 , FCC, FCR
      PRINT 450 , NCOND, NCYL, NROD
         IF ( NCOND. NE. ISELF ) GO TO 900
      PRINT 460 , ( NODE1( I ), XORD1( I ), NODE2( I ), XORD2( I )  ,
     1                I = 1 , IFLAG1 )
  900 PRINT 475
      PRINT 480 , ( NODCY( J), LCEXY( J ), LCEXZ( J ), ECXYA(J),
     1                ECXZA( J ) , APMOY1( J ), APMOZ1( J ),J =1,IFLAG2 )
         IF( NAXCON . EQ . NCONS   ) GO TO 960
      PRINT 494
      PRINT 495, ( IMR , AXMULT( IMR ), IMR = 1 , NUMNP        )
         GO TO 965
  960 PRINT 490
  965     IF ( LPRTP .EQ. 1 .AND. FS .LT. ONE ) GO TO 910
          IF ( LPRTP .EQ. 1 ) PRINT 510, FS, LFSTP
          GO TO 920
  910 PRINT 500
  920     IF ( LPRTP .EQ. 2 ) PRINT 520, OPPRE
          IF ( LPRTP .EQ. 3 ) PRINT 530, OPPRE, ALTH, ALF
      RETURN
C
C---- >>> DIAGONOSTICS FOR ILLEGAL INPUTS
C
 1000 PRINT 550
          GO TO 1600
 1100 PRINT 560
          GO TO 1600
 1200 PRINT 570
 1600 PRINT 580
 1700 PRINT 590
C
C---- >>> END OF RUN IF ERROR IN INPUT IS ENCOUNTERED
C
      STOP
      END
```

```
      SUBROUTINE DIST
     1           ( NCYL, NROD, NCOND, IFLAG1, IFLAG2, NPMAX, NELMAX,
     1           MLONG, MWIDE, GC, EXL ,LPRTP, RPC,
     C           X, NPCODE , ECXY, ECXZ, APMOY ,APMOZ                          )
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / ELEM    / NUMEL,NUMNP, NOCYE, NGL, NGLA
      COMMON /  ORD1   / NODE1( 10), XORD1( 10), NODE2( 10), XORD2(10)
      COMMON /  TEMP   / NODCY( 10), LCEXY( 10), LCEXZ( 10), ECXYA( 10 ),
     *                   ECXZA( 10), KODEXY( 10), KODEXZ( 10), APMOY1(10),
     *                   APMOZ1( 10 )
      COMMON / LENGTS / STROK, PHL, SBL, EPTK, CHDS, LFLUID
      COMMON / STPTBS / CL, RL, STPTB
      DIMENSION X( NPMAX ), ECXY( NPMAX ), ECXZ( NPMAX ), NPCODE( NPMAX)
     *           ,APMOY( NPMAX ), APMOZ( NPMAX )
      DATA ZERO , TWO / 0.00000, 2.00000 /
      DATA ISELF /4HSELF /
                 NUMEL    = NCYL + NROD
                 NUMNP    = NUMEL + 1
                 NOCYE      = NCYL - 1
                 NGL      = NOCYE + 1
                 NGLA     = NGL + 1
                 EFCL     = CHDS + EPTK + STROK
         IF( LPRTP . NE. 3 ) GO TO 300
                 RL       = STROK + SBL + GC + RPD / 2.00000
                 CL       = STROK + PHL + GC
                 EXL      = CL + EPTK + CHDS + RL - GC
  300 CONTINUE
                 EFRD     = RL - GC - SBL
                 EFGL     = GC + PHL + SBL
                 XGLA     = EFCL + EFGL
                 XGL      = EFCL + ( EFGL / TWO )
                 DENOM1   = NCYL - 2
                 DENOM2   = NROD
                 DXCY     = EFCL / DENOM1
                 DXRD     = EFRD / DENOM2
      DO 400 J = 1, NUMNP
                 X ( J ) = ZERO
               NPCODE (J)= ZERO
              ECXY( J )  = ZERO
               ECXZ( J ) = ZERO
             APMOY( J )  = ZERO
             APMOZ( J )  = ZERO
  400 CONTINUE
          IF ( NCOND . EQ. ISELF ) GO TO 1000
C
C--- >>> CO-ORDINATE DATA FOR AUTO OPTIONS
C
      DO 800 I = 2, NUMNP
          IF ( I . GT. NOCYE ) GO TO 600
                 X ( I ) = X( I - 1 ) + DXCY
          GO TO 800
  600            CONTINUE
          IF ( I . EQ. NGL ) X( I ) = XGL
          IF ( I . EQ. NGLA ) X ( I ) = XGLA
          IF( I. EQ. NGL.OR. I.EQ.NGLA ) GO TO 800
                 X( I ) = X( I - 1 ) + DXRD
  800 CONTINUE
          GO TO 1300
C
C---- >>>> CO-ORDINATE DATA FOR SELF OPTION
C
 1000 DO 1200 I = 1 ,IFLAG1
                 NEL        = NODE2( I ) - NODE1( I )
                 DENOM      = NEL
            IF ( NODE1( I ) . EQ. NOCYE ) XORD1( I ) = EFCL
            IF ( NODE1( I ) . EQ. NGL   ) XORD1( I ) = XGL
            IF ( NODE1( I ) . EQ. NGLA  ) XORD1( I ) = XGLA
            IF ( NODE2( I ) . EQ. NOCYE ) XORD2( I ) = EFCL
            IF ( NODE2( I ) . EQ. NGL   ) XORD2( I ) = XGL
            IF ( NODE2( I ) . EQ. NGLA  ) XORD2( I ) = XGLA
            IF ( NODE2( I ). EQ. NUMNP  ) XORD2( I ) = EXL
                 DX         = ( XORD2( I ) - XORD1( I )) / DENOM
                 ISTRT      = NODE1( I ) + 1
                 ISTOP      = NODE2( I ) - 1
           X( ISTRT - 1 )= XORD1( I )
        DO 1100 II = ISTRT , ISTOP
                 X ( II )= X( II - 1 ) + DX
 1100 CONTINUE
              X( ISTOP+1)= XORD2 ( I )
 1200 CONTINUE
C
C--- >>> DISTRUBUTE THE ELASTIC CONSTRAINTS
 1300 DO 1400 J = 1, IFLAG2
                 ISTA       = NODCY( J )
                 IKODE      = 2 * KODEXY( J ) + KODEXZ( J )
          NPCODE( ISTA ) = IKODE
              ECXY( ISTA )= ECXYA ( J )
               ECXZ(ISTA) = ECXZA ( J )
            APMOY( ISTA ) = APMOY1 ( J )
            APMOZ( ISTA ) = APMOZ1 ( J )
 1400 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CONST
     1           ( ECYL, ERCD, CHDS, LANGU,
     C             CYI , RDI, CYK, RDK                                    )
C
C---- >>> SUBROUTINE TO CALCULATE CONSTANT TERMS FOR CONVENIENCE
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / BRGSTF / PRKX, SPRK, RBKY, SRBK
      COMMON / CRPROP / RDZ, CYZ, RDZI, CYZI, HSCCI, HSCCO, HSCRI,
     *                  HSCRO, BAREAC, BAREAR, CAREAC, CAREAR
      COMMON / CLEAR  / PCL, RCL
      COMMON / CLERNC / CSBC, PCL1, RCL1
      COMMON / DIAMTS / COD, CID, ROD, RID, CPD, RPD, PHD, SBD
      COMMON / ERCONS / ECCY, ECRD
      COMMON / INCLER / CINCL, ECC, ECR
      COMMON / PISTON / PRW(5), PRT(5), PRE(5), PPK(5), PRDST(5), NPHBR
      COMMON / RODBRS / RBW(5), RBT(5), RBE(5), RBK(5), RBDST(5), NRDBR
      COMMON / WGTCON / WPH, WSB
      COMMON / WGTINI / WC1, WR1, WPH1, WSB1
      COMMON / WGTVER / WC, WR
C
      DATA ZERO, TWO, FOUR, SXTFOR / 0.0000, 2.0000, 4.0000, 64.0000 /
      DATA H180 /180.00000 /
      DATA PI / 3.14159265358979300O /
      DATA LDEG / 4HDEG /
C
C---- >>> CALCULATE STIFFNESSES OF BEARINGS AND SEALS IF NOT INPUT
C
               SPRK   = ZERO
               PRKX   = ZERO
         DO 110 I = 1, NPHBR
         IF ( PPK(I) .GT. ZERO ) GO TO 100
               PPK(I) = CID * PRW(I) * PRE(I) / PRT(I)
  100          PRKX   = PPK(I) * PRDST(I) + PRKX
  110          SPRK   = PPK(I) + SPRK
               SRBK   = ZERO
               RBKY   = ZERO
         DO 130 I = 1, NRDBR
         IF ( RBK(I) .GT. ZERO ) GO TO 120
               RBK(I) = ROD * RBW(I) * RBE(I) / RBT(I)
  120          RBKY   = RBK(I) * RBDST(I) + RBKY
  130          SRBK   = RBK(I) + SRBK
C
C---- >>> CALCULATE CROSS SECTIONAL PROPERTIES
C
               ROD2   = ROD * ROD
               RID2   = RID * RID
               COD2   = COD * COD
               CID2   = CID * CID
               CYI    = PI * ( COD2 * COD2 - CID2 * CID2 ) / SXTFOR
               RDI    = PI * ( ROD2 * ROD2 - RID2 * RID2 ) / SXTFOR
               RDZ    = RDI * TWO / ROD
               CYZ    = CYI * TWO / COD
               RDZI   = 1.0D+20
         IF ( RID .GT. ZERO ) RDZI = RDI * TWO / RID
               CYZI   = CYI * TWO / CID
C
C---- >>> BORE AREAS AND CROSS SECTIONAL AREAS OF CYLINDER AND ROD
C
               BAREAC = PI * CID2 / FOUR
               BAREAR = PI * RID2 / FOUR
               CAREAC = PI * ( COD2 - CID2 ) / FOUR
               CAREAR = PI * ( ROD2 - RID2 ) / FOUR
C
C---- >>> CALCULATE HOOP STRESS COEFFICIENT
C
               RDENC  = COD2 - CID2
               HSCCI  = ( COD2 + CID2 ) / RDENC
               HSCCO  = TWO * CID2 / RDENC
               RDENR  = ROD2 - RID2
               HSCRI  = ( ROD2 + RID2 ) / RDENR
               HSCRO  = TWO * RID2 / RDENR
C
               CYK    = DSQRT ( ECYL * CYI )
               RDK    = DSQRT ( ERCD * RDI )
C
C---- >>> CALCULATE CLEARANCES AT PISTON HEAD AND STUFFING BOX
C
               PCL    = ( CID - PHD ) / TWO
         IF ( PCL1 .GT. ZERO ) PCL = PCL1
               RCL    = ( SBD - ROD ) / TWO + CSBC
         IF ( RCL1 .GT. ZERO ) RCL = RCL1 + CSBC
C
C---- >>> CALCULATE VERTICAL COMPONENTS OF WEIGHTS
C
               TEMP   = PI / H180
               BETA3  = CINCL
         IF( LANGU.EQ.LDEG ) BETA3 = CINCL * TEMP
               CB      = DCOS ( BETA3 )
               WC     = WC1 * CB
               WR     = WR1 * CB
               WPH    = WPH1 * CB
               WSB    = WSB1 * CB
C
      RETURN
      END
```

```
      SUBROUTINE TRIALP
     I            ( ERQD, LPRTP, RDI, FYCYL, BAREAC, HSCCI, FYROD,
     I             BAREAR, HSCRI , EXL , AXMULT, NPMAX ,NUMNP,
     O              PINCR1, PINCR2, P12                                 )
C
C---- >>> SUBROUTINE TO CALCULATE TRIAL LOAD AND LOAD INCREMENTS
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / LENGTS / STROK, PHL, SBL, EPTK, CHDS, LFLUID
C
      DATA TWO, FIFTY, FIVHUN / 2.0D00, 50.0D00, 500.0D00 /
      DATA PI / 3.14159265358979300O /
      DATA LYES/ 3HYES/
      DIMENSION AXMULT ( NPMAX )
C
C---- >>> IF LPRTP = 3 CALCULATE APPROXIMATE EXTENDED LENGTH
C
            IF ( LPRTP - 3 ) 110, 100, 110
  100              EXL      = STROK + STROK + PHL + SBL + CHDS + EPTK
C
C---- >>> TRIAL LOAD (1) AS PER EULERS BUCKLING, CONSIDERING FULL
C            LENGTH STIFFNESS AS THAT OF ROD ONLY
C
  110              P12      = PI * PI * EROD * RDI / ( EXL * EXL )
C
C---- >>> TRIAL LOAD (2) AS PER EXCESSIVE HOOP STRESS RESTRICTION IN CYL
C
                   P2       = FYCYL * BAREAC / HSCCI
C
C---- >>> TRIAL LOAD (3) AS PER EXCESSIVE HOOP STRESS RESTRICTION IN ROD
C
                   P3       = FYROD * BAREAR / HSCRI
            IF ( LFLUID .NE. LYES ) P3 = P2
C
C---- >>> TRIAL LOAD, SMALLER OF (1), (2) AND (3)
C
                   P12      = DMIN1( P12, P2, P3 )
C
C >>>>   CALCULATE TRIAL LOAD FOR CYLINDERS WITH VARIABLE AXIAL LOADS
C
                   DAX       = 1.000D0
      DO 200 I = 1 , NUMNP
         IF( AXMULT( I ) . GT. DAX ) GO TO 150
         GO TO 200
  150              DAX       = AXMULT( I )
  200 CONTINUE
                   P12       = P12 / DAX
C
C---- >>> CALCULATE LOAD INCREMENTS
C
                   PINCR1 = P12/ FIFTY
                   PINCR2 = P12/ ( FIVHUN * TWO )
      RETURN
      END
```

```
      SUBROUTINE EQSTIF
     I          ( P, MWIDE, MLONG, X, CYI, RDI, EXL, NPMAX, NELMAX,NPCODE
     I           ,ECXY, ECXZ, MBAND, RHOC, BETA,KITER,AXMULT,APMOY,APMOZ,
     O             A , B, PI                                               )
      IMPLICIT REAL * 8 ( A - H, O - Z )
      DIMENSION NPC( 2 ), A( MLONG, MWIDE ), B( MLONG ), LM( 2 ),
     1           SQD( 8   ,   8 ), NPCODE( NPMAX ), X( NPMAX ),
     2           ECXY( NPMAX ), ECXZ( NPMAX ), BS(  8 ), AXMULT( NPMAX ),
     2           APMOY( NPMAX ), APMOZ( NPMAX ), PI( NPMAX )
      COMMON / ELEN    / NUMEL,NUMNP, NOCYE, NGL, NGLA
      COMMON / INCLFR / CINCL, FCC, FCR
      COMMON / PROPTS / ECYL, EROD, FYCYL, FYROD
      COMMON / CRPROP / RDZ, CYZ, RDZI, CYZI, HSCCI, HSCCO, HSCRI,
     *                  HSCRO, BAREAC, BAREAR, CAREAC, CAREAR
      COMMON / WGTCON / WPH, WSB
      COMMON / WGTVER / WC, WR
      DATA ZERO / 0.00D00 /
C
      DO 100 I = 1 , NPMAX
                PI( I ) = 0.0D00
  100 CONTINUE
C
C  >>>>>  CALCULATE NODAL AXIAL FORCES
C
      DO 200 ICK = 1 , NUMNP
              PI( ICK ) = AXMULT( ICK ) * P
  200 CONTINUE
C >>>>> INTIALIZE MATRICES
C
      DO 400 I = 1 , MLONG
                B( I )   = ZERO
      DO 400 J = 1, MWIDE
        A ( I, J )       = ZERO
  400 CONTINUE
C
C---- >>>> FORM STIFFNESS MATRIX
C
      DO 800 N = 1 , NUMEL
              NPC( 1 )    = N
              NPC( 2 )    = N + 1
      CALL STIFF
     I          ( X, CYI, RDI, NPC, NPMAX, PI,
     O            SQD, BS, RCONS, SCONS , CONS                            )
C
C ---- >>>> FORM THE RIGHT HAND SIDE
C
                KJ        = 4 * ( N - 1 )
              B( KJ+1 ) = B( KJ + 1 ) + BS( 1 )
              B( KJ+4 ) = B( KJ + 4 ) + BS( 4 )
              B( KJ+5 ) = B( KJ + 5 ) + BS( 5 )
              B( KJ+8 ) = B( KJ + 8 ) + BS(  8 )
          IF( KITER. EQ. 1 ) GO TO 450
          IF(NPC(1). NE. NGL) GO TO 450
              B( KJ+1 ) = B( KJ + 1 ) - RCONS * BETA
              B( KJ+2 ) = B( KJ + 2 ) - SCONS * RHOC
              B( KJ+3 ) = B( KJ + 3 ) + RCONS * RHOC
              B( KJ+4 ) = B( KJ + 4 ) - SCONS * BETA
              B( KJ+5 ) = B( KJ +  5) + RCONS * BETA
```

```
              B( KJ+6 ) = B( KJ + 6 ) - CONS * RHOC
              B( KJ+7 ) = B( KJ + 7 ) - FCONS * PHOC
              B( KJ+8 ) = B( KJ + 8 ) - CONS * BETA
C
C---- >>> ADD TO TOTAL STIFFNESS MATRIX
C
  450 DC 500 IJ = 1 , 2
              LM( IJ )    = 4 * ( NPC( IJ ) - 1 )
  500 CONTINUE
      DO 700 I = 1 , 2
      DG 700 K = 1 , 4
                II        = LM ( I ) + K
                KK        = 4 * ( I - 1 ) + K
      DO 700 J = 1 ,2
      DO 700 L = 1, 4
                JJ        = LM( J ) + L - II + 1
          IF ( JJ. LE. 0 ) GO TO 600
                LL        = 4 * ( J - 1 ) + L
             A( II, JJ )= A( II , JJ ) + SQD ( KK, LL )
  600 CONTINUE
  700 CONTINUE
  800 CONTINUE
C
C---- >>>> CALCULATE FRICTION TERMS
C
                FRCCNS   = ( P * ( FCR - FCC )) / EXL
                FCMOM    = P1( 1 ) * FCC
                FRMOM    = P1( NUMNP ) * FCR
C
C---- >>>> ADD FRICTIONAL TERMS TO R . H. S
C
      DO 1400 N = 1 , NUMNP
                K         = 4 * ( N - 1 )
                KEY       = NPCODE( N ) + 1
          GO TO( 1300,900,1100,900,1100,900,1300 ) , KEY
  900    IF( ECXZ( N ). EO. ZERO ) GO TO 1050
          IF( N . GT . NGLA ) GO TO 1C00
           B ( K + 3)   = B( K + 3 ) - FRCONS
           B ( K + 2 ) = B( K + 2 ) - FCMOM
          IF( KEY.EQ.2.OR.KEY.EQ.6 ) GO TO 1300
 1000      B( K + 3 )   = B( K + 3 ) + FRCONS
           B( K + 2 )   = B( K + 2 ) + FRMOM
 1050     IF( KEY.EQ.2.OR.KEY.EQ.6 ) GO TO 1300
 1100 •   IF( N.GT.NGLA ) GO TO 1200
           B( K+ 1)      = B( K + 1 ) - FRCONS
           B( K + 4 )   = B( K + 4 ) - FCMOM
          GO TO 1300
 1200      B( K + 1 )   = B( K + 1 ) + FPCONS
           B ( K + 4 ) = B( K + 4 ) + FRMOM
 1300 CONTINUE
           B ( K + 2 ) = B ( K + 2 ) + P * ECXZ( N )+ APMOY( N )
           B ( K + 4 ) = B( K + 4 ) + P * ECXY (N )    + APMOZ( N )
 1400 CONTINUE
C
C ---- >>>> REVISE FOR SPECIFIED DISPLACEMENTS
C
      DO 2200 N = 1 , NUMNP
                KEY       = NPCODE( N ) + 1
          GO TO ( 1600,1600,1500,1500,1500,1500,1500 ), KEY
 1500           M         = 4 * N - 3
                U         = ZERO
      CALL MOD( A, B, MLONG, MWIDE, MBAND, M , U )
 1600     GO TO( 1800,1800,1800,1800,1700,1800,1700), KEY
 1700           M         = 4 * N - 2
                U         = ZERO
      CALL MOD( A, B, MLONG, MWIDE, MBAND, M , U )
 1800     GO TO ( 2000,1900,2000,1900,1900,1900,1900), KEY
 1900           M         = 4 * N - 1
                U         = ZERO
      CALL MOD( A, B, MLONG, MWIDE, MBAND, M , U )
 2000     GO TO ( 2200,2200,2200,2200,2200,2100,2100 ), KEY
 2100           M         = 4 * N
                U         = ZERO
      CALL MOD( A, B, MLONG, MWIDE, MBAND, M , U )
 2200 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STIFF
     1          ( X, CYI, RDI, NPC, NPMAX, P1,
     C            S, BS, RCONS, SCONS, CONS                             )
C
C   >>>> SUBROUTINE TO FORMULATE THE STIFFNESS MATRIX
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / ELEN   / NUMEL,NUMNP, NOCYE, NGL, NGLA
      COMMON / PROPTS / ECYL, EROD, FYCYL, FYROD
      COMMON / WGTVER / WC, WR
      COMMON / WGTCON / WPH, WSB
      COMMON / CRPROP / RDZ, CYZ, RDZI, CYZI, HSCCI, HSCCO, HSCRI,
     *                  HSCRO, BAREAC, BAREAR, CAREAC, CAREAR
      DATA ZERO, ONE, TWO, TRE, FOUR, SIX/ 0.C0000,1.C0D00,2.00D00,
     *                                   3.00D00, 4.C0D00, 6.00D00 /
      DIMENSION S( 8 , 8 ), NPC( 2 ), BS( 8), X( NPMAX ), P1( NPMAX )
      DO 100 I = 1 , 8
             BS( I ) = ZERO
      DO 100 J = 1 , 8
         S( I, J )   = ZERO
  100 CONTINUE
             N        = NPC( 1 )
             XLEN     = X ( N + 1 ) - X ( N )
             XLEN2    = XLEN * XLEN
             XLEN3    = XLEN2 * XLEN
          IF ( NPC( 2 ) . GT . NGL ) GO TO 200
             AREA     = CAREAC
             AINE     = CYI
             E        = ECYL
        GO TO 300
  200        AREA     = CAREAR
             AINE     = RDI
             E        = EROD
  300 CONTINUE
             AXTE     = AREA * E / XLEN
             PHI2     = P1( N ) * XLEN2 / ( E * AINE )
             PHI      = DSQRT( PHI2 )
             PHIA4    = PHI2 / FOUR
             ALFA     = -SIX * ( ONE -( PHI/DSIN(PHI)))/PHI2
             ALFA2    = ALFA * ALFA
             BETA1    = TRE * ( ONE - ( PHI / DTAN( PHI ))) / PHI2
             BETA2    = BETA1 * BETA1
             TBET     = BETA1 * TWO
             CA       = ALFA / TBET
             DENOM    = FOUR * BETA2 - ALFA2
             AK       = TRE * BETA1/ DENOM
             KAT      = FOUR * E * AINE / XLEN
             KAT2     = KAT / XLEN
             KAT3     = KAT / XLEN2
             SCONS    = AK * KAT
             CONS     = CA * SCONS
             PHI3     = PHI2 * PHI
             SPHI     = DSIN( PHI )
             CPHI     = DCOS( PHI )
             DENOM    = XLEN3 * ( TWO - TWO * CPHI - PHI*SPHI)
             ANVR     = PHI3 * SPHI * AINE * E
             TCONS    = ANVR / DENOM
             ANVR1    = -PHI2 * ( CPHI - ONE ) * XLEN * E* AINE
             RCONS    = ANVR1 / DENOM
         S( 1 , 1 ) = TCONS
         S( 1 , 4 ) = RCONS
         S( 1 , 5 ) = -TCONS
         S( 1 , 8 ) = RCONS
         S( 2 , 2 ) = SCONS
         S( 2 , 3 ) = -RCONS
         S( 2 , 6 ) = CONS
         S( 2 , 7 ) = RCONS
         S( 3 , 3 ) = TCONS
         S( 3 , 6 ) = -RCONS
         S( 3 , 7 ) = -TCONS
         S( 4 , 4 ) = SCONS
         S( 4 , 5 ) = -RCONS
         S( 4 , 8 ) = CONS
         S( 5 , 5 ) = TCONS
         S( 5 , 8 ) = -RCONS
         S( 6 , 6 ) = SCONS
         S( 6 , 7 ) = RCONS
         S( 7 , 7 ) = TCONS
         S( 8 , 8 ) = SCONS
C
C---- >>>> FORM SYMMETRIC MATRIX
C
      DO 600 I = 1, 8
      DO 500 J = 1, 8
             S( J,I )  = S( I , J )
  500 CONTINUE
  600 CONTINUE
C
C ---- >>>> FORM THE RIGHT HAND SIDE
C
             WPHE     = WC + WPH
             WSBE     = WR + WSB
         IF( NPC(2). LE. NOCYE) WT = WC
         IF( NPC(2) . EQ . NGL) WT = WPHE
         IF( NPC(2) . EQ. NGLA) WT = WSBE
         IF( NPC(2). GT. NGLA ) WT = WR
             DELC     = PHI * ( TWO - TWO * DCOS( PHI) - PHI *
     *                  DSIN( PHI ))
             CONS1    = TWO * DSIN( PHI ) - PHI * DCOS( PHI ) - PHI
             WL2      = WT * XLEN2
             WL2A     = WL2 / TWO
             BS( 1 ) = -WT * XLEN / TWO
             BS( 4 ) = WL2A * CONS1 / DELC - WL2 / PHI2
             BS( 5 ) = -WT * XLEN / TWO
             BS( 8 ) = -WL2A * CONS1 * CPHI/ DELC-
     *                 WL2A * SPHI / PHI + WL2 / PHI2
      RETURN
      END
```

```
      SUBROUTINE MULT ( X, Y, Z, M, N, K )
C
C   >>>> SUBROUTINE TO PERFORM MATRIX MULTIPLICATION.
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      DIMENSION X( M, N ) , Y( N, K ), Z( M, K )
      DATA ZERO / 0.00D00 /
      DO 110 I = 1 , M
      DO 110 J = 1, K
               TEMP     = ZERO
      DO 100 L = 1 , N
               TEMP     = TEMP + X( I , L ) * Y( L , J )
  100 CONTINUE
            Z( I , J) = TEMP
  110 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE MOD ( A,B, MLONG ,MWIDE, MBAND, M, U                  )
C
C   >>>> SUBROUTINE TO MODIFY THE OVERALL STIFFNESS MATRIX
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      DIMENSION A( MLONG, MWIDE ) , B( MLONG )
      DATA ZERO, ONE /0.00D00 , 1.00D00 /
      DO 110 I = 2, MBAND
               K         = M - I + 1
          IF( K . LE. 0 ) GO TO 100
               B( K )    =B( K ) - A(K, I ) * U
             A( K, I ) = ZERO
  100          K         = M + I - 1
          IF( MLONG . LT. K ) GO TO 110
               B( K )    = B( K ) - A( M, I ) * U
               A( M, I ) = ZERO
  110 CONTINUE
           A( M , 1)     = ONE
               B( M )    = U
      RETURN
      END
```

```
      SUBROUTINE BANSOL ( B , A , MBAND, MWIDE, MLONG, CD, MLONG1        )
C
C >>>> SUBROUTINE TO SOLVE BANDED MATRIX
C
      IMPLICIT REAL * 8 ( A-H, O-Z )
      DIMENSION B( MLONG ), A( MLONG, MWIDE ), CD( MLONG )
      DATA ZERO / 0.0000 /, ONE / 1.0000 /
  130 DO 160 N = 1 , MLONG1
         IF ( A(N,1) .EQ. ZERO ) GO TO 160
            TEMP = ONE / A(N,1)
            B(N) = TEMP * B(N)
         DO 150 M = 2, MBAND
         IF ( A(N,M) .EQ. ZERO ) GO TO 150
            C = A(N,M) * TEMP
            I = N + M - 1
            J = 0
         DO 140 K = M, MBAND
            J = J + 1
            A(I,J) = A(I,J) - C * A(N,K)
  140    CONTINUE
            B(I) = B(I) - A(N,M) * B(N)
            A(N,M) = C
  150    CONTINUE
  160    CONTINUE
  170 DO 190 M = 1 , MLONG1
            N        = MLONG1+ 1 - M
         DO 180 K = 2, MBAND
            L = N + K - 1
            B(N) = B(N) - A(N,K) * B(L)
  180    CONTINUE
            NM       = N + MLONG1
            B(NM) = B(N)
            CD( N ) = B( N )
  190    CONTINUE
            MLONG2  = MLONG1 + 1
      DO 200 KL = MLONG2, MLONG
            CD( KL ) = ZERO
  200 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE THETA
     I          ( PRK, PRDST, RBK, RBDST, NPHBR, NRDBR, GC, BMG,
     I            PHL, SBL,
     O            XGL, YGL, TETA                                    )
C
C---- >>> SUBROUTINE TO CALCULATE CROCKEDNESS ANGLE AND FORCES AT
C         INTERFACE
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / BRGSTF / PRKX, SPRK, RBKY, SRBK
      COMMON / CLEAR  / PCL, RCL
      COMMON / GLDFOR / FX(5), FY(5), F1, F2, F3, F4
C
      DIMENSION PRK( NPHBR ), PRDST( NPHBR ), RBK( NRDBR ),RBDST(NRDBR)
C
      DATA ZERO, ONE, TWO / 0.0000, 1.0000, 2.0000 /
C
C
C---- >>> MONITOR FOR PROPER SIGN
C
              SIGN    = ONE
         IF ( BMG ) 100, 110, 100
  100         SIGN    = BMG / DABS( BMG )
  110         SRPBK   = SRBK + SPRK
              F1      = ZERO
              F2      = ZERO
              F3      = ZERO
              F4      = ZERO
C
C---- >>> CASE 1:  NO METAL TO METAL CONTACT AT SLIDING CONNECTION
C
              XGL      = ( RBKY + GC * SRBK - PRKX ) / SRPBK
              YGL       = GC - XGL
         IF ( PCL .EQ. ZERO .AND. RCL .EQ. ZERO ) GO TO 690
              CF      = ZERO
         DO 130 I = 1, NPHBR
  130         CF        = CF + PRK( I ) * (XGL + PRDST(I)) *
     *                      ( XGL + PRDST( I ) )
         DO 140 I = 1, NRDBR
  140         CF        = CF + RBK( I ) * ( YGL + PBDST( I ) ) *
     *                      ( YGL + RBDST( I ) )
              TETA    = BMG / CF
              D1        = ( XGL + PHL ) * DABS ( TETA )
              D2        = ( YGL + SEL ) * DABS( TETA )
         IF ( D1 .GE. PCL .AND. D2 .GE. RCL ) GO TO 170
         IF ( D1 - PCL ) 150, 200, 200
  150    IF ( D2 - PCL ) 750, 300, 300
  170         D22        = PCL * ( YGL + SBL ) / ( XGL + PHL )
         IF ( D22 - RCL ) 200, 300, 300
C
C---- >>> CASE 2:  CONTACT AT FRONT FACE OF PISTON HEAD
C
  200         XNUM    = ZERO
              XDEN    = ZERO
              AGL     = PHL + GC
              BGL     = DABS( BMG ) / PCL
         DO 210 I = 1, NPHBR
              TEMP    = PRK(I) * ( PHL - PRDST(I) )
```

```
            XDEN     = XDEN + TEMP
  210       XNUM     = XNUM + TEMP * PRDST( I)
            XNUM     = - XNUM
        DO 220 I = 1, NRDBR
            TEMP      = RBK( I ) + ( AGL * RBDST( I ))
            XDEN     = XDEN + TEMP
  220       XNUM     = XNUM + TEMP * ( GC + RBDST(I) )
            XNUM     = XNUM - BGL * PHL
            XDEN      = BGL + XDEN
            XGL      = XNUM / XDEN
            YGL       = GC - XGL
            TETA      = PCL / ( XGL + PHL ) * SIGN
            D3       = DABS( TETA * XGL )
            D2        = ( YGL + SBL ) * DABS ( TETA )
        IF ( D3 .GE. PCL .AND. D2 .GE. RCL ) GO TO 270
        IF ( D3 - PCL ) 240, 400, 400
  240   IF ( D2 - RCL ) 250, 600, 600
  250       F1        = TETA -( RBKY + GC * SRBK - PRKX - XGL*SRPBK  )
        GO TO 750
  270       TETA     = PCL * TWO / PHL
            D2       = ( PHL / TWO + GC + SBL ) * TETA
        IF ( D2 - RCL ) 400, 600, 600
C
C---- >>> CASE 3:  CONTACT AT FRONT FACE OF STUFFING BOX
C
  300       XNUM     = ZERO
            XDEN     = ZERO
            AGL      = SBL + GC
            BGL      = DABS( BMG ) / RCL
        DO 310 I = 1, NPHBR
            TEMP      = PRK( I ) * ( AGL + PRDST( I ) )
            XDEN     = XDEN + TEMP
  310       XNUM     = XNUM + TEMP * PRDST(I)
            XNUM     = - XNUM
        DO 320 I = 1, NRDBR
            TEMP     = RBK(I) * ( SBL - RBDST(I) )
            XDEN     = XDEN + TEMP
  320       XNUM     = XNUM + TEMP * ( GC + RBDST(I) )
            XNUM      = XNUM + BGL * AGL
            XDEN      = BGL + XDEN
            XGL      = XNUM / XDEN
            YGL       = GC - XGL
            TETA      = RCL / ( YGL + SBL ) * SIGN
            D1        = ( XGL + PHL ) * DABS ( TETA )
            D4       = DABS( TETA * YGL )
        IF ( D1 .GE. PCL .AND. D4 .GE. RCL ) GO TO 370
        IF ( D1 - PCL ) 340, 600, 600
  340   IF ( D4 - RCL ) 350, 500, 500
  350       F2        = TETA * ( XGL * SRPBK -RBKY-GC*SRBK+PRKX )
        GO TO 750
  370       TETA     = RCL * TWO / SBL
            D1       = ( PHL + GC + SBL / TWO ) * DABS( TETA )
        IF ( D1 - RCL ) 500, 600, 600
C
C---- >>> CASE 4:  CONTACT AT FRONT AND BACK FACES OF PISTON HEAD
C
  400       XGL      = - PHL / TWO
            TETA     = TWO * PCL / PHL * SIGN
            YGL       = GC - XGL
      CALL GFORCE ( PRK, PRDST, TETA, XGL, NPHBR,                FX )
      CALL GFORCE ( RBK, RBDST, TETA, YGL, NRDBR,                FY )
          DO 470 I = 1, NPHBR
            F3       = F3 + FX(I)
  470       F1       = F1 + FX(I) * PRDST(I)
          DO 480 I = 1, NRDBR
            F3       = F3 - FY(I)
  480       F1       = F1 + FY(I) * ( GC + RBDST(I) )
            F1       = ( BMG - F1 ) / PHL
            F3       = F1 + F3
      RETURN
C
C---- >>> CASE 5:  CONTACT AT FRONT AND BACK FACES OF STUFFING BOX
C
  500       XGL      = GC + SBL / TWO
            TETA     = TWO * RCL / SBL * SIGN
            YGL       = GC - XGL
      CALL GFORCE ( PRK, PRDST, TETA, XGL, NPHBR,                FX )
      CALL GFORCE ( RBK, RBDST, TETA, YGL, NRDBR,                FY )
          DO 570 I = 1, NPHBR
            F2       = - FX(I) * ( GC + PRDST(I) ) + F2
  570       F4       = - FX(I) + F4
          DO 580 I = 1, NRDBR
            F2       = F2 - FY(I) * RBDST(I)
  580       F4       = F4 + FY(I)
            F2       = ( BMG + F2 ) / SBL
            F4       = F2 + F4
      RETURN
C
C---- >>> CASE 6:  CONTACT AT FRONT FACE OF PISTON HEAD AND FRONT FACE
C                  OF STUFFING BOX
C
  600       TETA     = ( PCL + RCL ) / ( PHL + GC + SBL ) * SIGN
            XGL      = PCL / DABS( TETA ) - PHL
            YGL       = GC - XGL
      CALL GFORCE ( PRK, PRDST, TETA, XGL, NPHBR,                FX )
      CALL GFORCE ( RBK, RBDST, TETA, YGL, NRDBR,                FY )
          DO 670 I = 1, NPHBR
            F1       = - FX(I) * ( SBL + GC + PRDST(I) ) + F1
  670       F2       = FX(I) + F2
          DO 680 I = 1, NRDBR
            F1       = F1 + FY(I) * ( SBL - RBDST(I) )
  680       F2       = - FY(I) + F2
            F1       = ( BMG + F1 ) / ( PHL + GC + SBL )
            F2       = F1 + F2
      RETURN
  690       TETA     = ZERO
C
  750 CALL GFORCE ( PRK, PRDST, TETA, XGL, NPHBR,                FX )
      CALL GFORCE ( RBK, RBDST, TETA, YGL, NRDBR,                FY )
      RETURN
      END
```

```
      SUBROUTINE GFORCE
     *          ( AK, DST, TETA, XGL, N,                          F )
C
C---- >>> SUBROUTINE TO CALCULATE FORCES ON EACH BEARING
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      DIMENSION AK(N), DST(N), F(N)
C
          DO 100 I = 1, N
                F ( I ) = AK ( I ) * ( XGL + DST( I ) ) * TETA
  100     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE GLAFOR
     1          ( X, CYI, RDI, CD, NPMAX, P1,MLONG,B,RHOC,BETA,KITER,
     1            FILOAD, P,
     C            GLFORC, BMG, GAMA                                    )
C
C     >>>> SUBROUTINE TO CALCULATE GLAND FORCES.
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / ELEM   / NUMEL,NUMNP, NOCYE, NGL, NGLA
      COMMON / PROPTS / ECYL, EROD, FYCYL, FYROD
      COMMON / WGTVER / WC, WR
      DIMENSION CD( MLONG ), GF( 8 ), GLFORC( 8 ), S( 8 , 8 ), NPC( 2 ),
     *          BS( 8   ) , X( NPMAX ) , B( MLONG ), P1( NPMAX )
      DATA ZERO, P5, PI2 / 0.00D00, 0.5D00, 1.571428D00 /
C
C ---- >>>> CALCULATE FORCES AND MOMENTS AT THE GLAND
C
      DO 300 IN = 1 , 2
               NPC( 1 )= NOCYE + IN - 1
               NPC( 2 )= NPC( 1 ) + 1
      CALL STIFF
     I          ( X, CYI, RDI, NPC, NPMAX, P1,
     C            S, BS, RCONS, SCONS, CONS                            )
               IJ       = 4 * ( NPC( 1) - 1 ) +1
      DO 100 I = 1 , 8
               GF( I ) = CD( IJ )
               IJ       = IJ + 1
  100 CONTINUE
         IF( NPC( 1). NE. NGL ) GO TO 160
               GF( 2 ) = GF( 2 ) + RHOC
               GF( 4 ) = GF( 4 ) + BETA
  160 CONTINUE
          CALL MULT( S, GF, GLFORC,  8 , 8 , 1 )
          IF( IN . NE.1 ) GO TO 200
               TEMP6    = -P5 * GLFORC( 6 )
               TEMP8    = -P5 * GLFORC( 8  )
      GO TO 300
  200        GLFORC( 6)=  TEMP6       + P5 * GLFORC( 2 )
            GLFORC( 8 )=     TEMP8      + P5 * GLFORC( 4 )
  300 CONTINUE
               GLFORC( 6 ) = - GLFORC( 6 )
               GLFORC( 8   ) = -GLFORC ( 8   )
C
C--- >>> CALCULATE MOMENT IN THE RESULTANT PLANE
C
               BMG      = DSQRT( GLFORC( 6 ) ** 2 + GLFORC( 8   ) **2 )
               SIGN     = 1.00D00
          IF ( GLFORC( 8   ) . EQ. ZERO ) GO TO 400
          IF ( GLFORC(   6 ) . EQ. ZERO ) GO TO 500
               GAMA1    = GLFORC( 6) / GLFORC( 8 )
               GAMA2    = DABS( GAMA1 )
               SIGN     = GAMA1 / GAMA2
               GAMA     = DATAN( GAMA1 )
          GO TO 600
  400          GAMA     = PI2
          GO TO 600
  500          GAMA     = ZERO
               SIGN     = GLFORC( 8   ) / DABS( GLFORC( 8   ))
```

```
  600 CONTINUE
              BMG     = SIGN * BMG
              KXY     = 4 * NGL - 3
              KXZ     = 4 * NGL -1
C
C  >>>>> TEST FOR BUCKLING
C
        IF ( P . NE .FILOAD ) GO TO 710
        IF( CD( KXY ) . EQ . ZERO ) GO TO 680
            YSIGN1 = CD( KXY ) / DABS( CD( KXY ))
        IF( CD( KXZ ) . EQ . ZERO ) GO TO 700
        GO TO 690
  680       YSIGN1  = 1.00D00
  690        ZSIGN1 = CD( KXZ ) / DABS( CD( KXZ ))
        GO TO 710
  700       ZSIGN1  = 1.00D00
  710   IF( KITER.NE.1 ) GO TO 800
        IF( CD( KXY ) . EQ . ZERO ) GO TO 720
            YSIGN2 = CD( KXY ) / DABS( CD( KXY ))
        IF( CD( KXZ ) . EQ . ZERO ) GO TO 740
        GO TO 730
  720       YSIGN2  = 1.00D00
  730        ZSIGN2 = CD( KXZ ) / DABS( CD( KXZ ))
        GO TO 750
  740       ZSIGN2  = 1.00D00
  750       AKXY    = YSIGN1 - YSIGN2
            AKXZ    = ZSIGN1 - ZSIGN2
        IF( AKXY.NE.ZERO ) GO TO 900
        IF( AKXZ.NE.ZERO ) GO TO 900
            YSIGN1 =  YSIGN2
            ZSIGN1 =  ZSIGN2
  800 RETURN
  900 PRINT 1000, P
 1000 FORMAT(/10X,33HTHE CYLINDER BUCKLED AT A LOAD OF,D10.3       )
      STOP
      END
```

```
      SUBROUTINE FORCES
     1          ( X, CYI, RDI, CD, NPMAX, MLONG,P1, RHOC, BETA,
     C            BMXY, SHXY, BMXZ, SHXZ, AMAXCY, NODEC,
     O            AMAXRD, NODER, DEXY, DEXZ                         )
C
C   >>>> SUBROUTINE TO CALCULATE NODAL FORCES.
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / ELEN   / NUMEL,NUMNP, NOCYE, NGL, NGLA
      COMMON / WGTCON / WPH, WSB
      COMMON / WGTVER / WC, WR
      COMMON / PROPTS / ECYL, EROD, FYCYL, FYROD
      DIMENSION BMXY( NPMAX),SHXY(NPMAX),BMXZ(NPMAX),SHXZ(NPMAX),
     *          NPC( 2 ), AR( 8 , 1 ), CD( MLONG ),
     *          AF( 8 ) , X( NPMAX ), S( 8 , 8 ), BS( 8 ) , DEXY(NPMAX)
     *         ,DEXZ( NPMAX ) , P1( NPMAX )
      DATA P5, ZERO, TWO / 0.5D00, 0.0D00, 2.00D00 /
      DO 100 J = 1 , NUMNP
            BMXY( J ) = ZERO
            SHXY( J ) = ZERO
            BMXZ( J ) = ZERO
            SHXZ( J ) = ZERO
  100 CONTINUE
      DO 130 IP = 1 , NUMNP
              NP      = 4 * ( IP - 1 ) + 1
              NJ      = NP + 2
            DEXY( IP) = CD( NP )
            DEXZ( IP) = CD( NJ )
  130 CONTINUE
              AMAXCY  = ZERO
              AMAXRD  = ZERO
      DO 1000 N = 1 , NUMEL
              NPC(1)  = N
              NPC(2)  =N+1
      CALL STIFF
     I          ( X, CYI, RDI, NPC, NPMAX, P1,
     C            S, BS, RCONS, SCONS, CONS                          )
              IJ      = 4 * ( N - 1 ) + 1
      DO 150 I = 1 , 8
            AR(I, 1 ) = CD( IJ )
              IJ      = IJ + 1
  150 CONTINUE
         IF( NPC( 1 ). NE. NGL ) GO TO 160
            AR(2 , 1 )= AR( 2, 1 ) + RHOC
            AR(4 , 1 )= AR( 4, 1 ) + BETA
  160 CALL MULT ( S, AR, AF, 8 , 8 , 1 )
         IF( N . NE. 1 ) GO TO 200
            BMXY( N)  = -P5 *AF( 4 )
            BMXZ( N)  = -P5 * AF( 2 )
  200 CONTINUE
            BMXZ( N ) = BMXZ( N ) - P5 * AF( 2 )
            BMXY( N ) = BMXY( N ) - P5 * AF( 4 )
            SHXY( N ) = AF( 1 )
            SHXZ( N ) = AF( 3 )
           BMXZ( N+1 )= BMXZ( N+ 1 ) + P5 * AF( 6 )
           BMXY( N+1 )= BMXY( N+ 1 ) + P5 * AF( 8  )
            SHXY(N+1) = -AF( 5 )
           SHXZ( N+1) = AF( 7 )
```

```
      IF( NPC( 1). NE. NUMEL) GO TO 400
         BMXY( N+1)= TWO * BMXY( N + 1 )
         BMXZ( N+1)= TWO * BMXZ( N + 1 )
400   IF( N. GT. NGL ) GO TO 700
         AMOMC    = DSQRT ( BMXZ( N ) * BMXZ( N ) + BMXY ( N ) *
     *                BMXY( N ) )
      IF( AMOMC . GT. AMAXCY ) GO TO 600
      GO TO 1000
600      AMAXCY   = AMOMC
         NODEC    = N
      GO TO 1000
700      AMOMR    = DSQRT ( BMXZ( N ) * BMXZ( N ) + BMXY ( N ) *
     *                BMXY( N ) )
      IF ( AMOMR . GT. AMAXRD ) GO TO 800
      GO TO 1000
800      AMAXRD   = AMOMR
         NODER    = N
1000 CONTINUE
     RETURN
     END
```

```
      SUBROUTINE MAXMOM
     I           ( NODEC, NODER, CYI, RDI, X,PI, BMXY, CD, MLONG,
     I             SHXY, BMXZ, SHXZ, NPMAX, DEXY, DEXZ, RHOC, BETA,
     C             AMAXCY, AMAXRD, XCM, XRM, DEFLC, DEFLR, PC, PR          )
C
C   >>>> SUBROUTINE TO LOCATE THE POSITION OF MAXIMUM MOMENTS
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / PROPTS / ECYL, EROD, FYCYL, FYROD
      COMMON / WGTVER / WC, WR
      COMMON / ELEN   / NUMEL,NUMNP, NOCYE, NGL, NGLA
      DIMENSION X( NPMAX), BMXY( NPMAX), SHXY( NPMAX), BMXZ( NPMAX ),
     *          SHXZ( NPMAX ), DEXY( NPMAX ), DEXZ( NPMAX ) ,
     *          PI( NPMAX )
      DIMENSION CD( MLONG ), CTS( 4, 4 ), FTS( 4 ), FTP( 4), FTD( 4 )
      DATA ONE, TWO / 1.0D000, 2.0D000 /
      DATA ZERO / 0.0D000 /
               AMAXCY  = 0.0D000
               AMAXRD  = 0.0D000
               IK      = NODEC - 1
               ESTIF   = ECYL * CYI
               W       = WC
               NTIMES  = 10
         IF( NODEC. EQ. NGL ) NLIT = 1
         IF( NODEC. NE. NGL ) NLIT = 2
               ICNTRL  = 1
         GO TO 400
300            IK      = NODER - 1
               ESTIF   = EROD * RDI
               W       = WR
               NLIT    = 2
               ICNTRL  = 2
400   DO 1500 I = 1 , NLIT
         IF( I. EQ. 2. AND. ICNTRL. EQ. 2 ) NTIMES= 30
               XLEN    = X( IK + 1 ) - X( IK )
               XLEN2   = XLEN * XLEN
               XLEN4   = XLEN2 * XLEN2
               PHI2    = ( PI( IK ) * XLEN2 ) / ESTIF
               PHI     = DSQRT( PHI2 )
               PHI4    = PHI2 * PHI2
               SPHI    = DSIN( PHI )
               CPHI    = DCOS( PHI )
               COTPHI  = CPHI / SPHI
               XPH2    = XLEN2 / PHI2
               XPH4    = XLEN4 / PHI4
               FFI     = W / ESTIF
               DELC    = PHI * ( TWO - TWO * CPHI - PHI * SPHI )
               ATERM1  = ( ONE - CPHI- PHI * SPHI )
               ATERM2  = CPHI - ONE
               ATERM3  = SPHI - PHI * CPHI
               ATERM4  = PHI - SPHI
          CTS( 1, 1 ) = -PHI * SPHI
          CTS( 1, 2 ) = XLEN * ATERM1
          CTS( 1, 3 ) = - CTS( 1 , 1 )
          CTS( 1, 4 ) = XLEN * ATERM2
          CTS( 2, 1 ) = - PHI * ATERM2
          CTS( 2, 2 ) = XLEN * ATERM3
          CTS( 2, 3 ) = -CTS( 2 , 1 )
```

```
      CTS( 2, 4 ) = XLEN * ATERM4
      CTS( 3, 1 ) = CTS( 1, 3 ) * PHI
      CTS( 3, 2 ) = XLEN * CTS( 2 , 1 )
      CTS( 3, 3 ) = -CTS( 3 , 1 )
      CTS( 3, 4 ) = CTS( 3 , 2 )
      CTS( 4, 1 ) = PHI * ATERM1
      CTS( 4, 2 ) = -CTS( 2 , 2 )
      CTS( 4, 3 ) = CTS( 2 , 1 )
      CTS( 4, 4 ) = -CTS( 2 , 4 )
  DO 420 ICT = 1, 4
  DO 420 JCT = 1, 4
      CTS(ICT, JCT) = CTS( ICT, JCT ) / DELC
420 CONTINUE
        KONS      = W * XLEN4 / ( TWO * PHI2*ESTIF * DELC )
        COND1     = KONS * DELC / PHI
        COND2     = KONS * ( TWO* SPHI - PHI * CPHI - PHI )
        COND3     = -KONS * DELC
        COND4     = -COND2
        NP        = 4 * ( IK - 1 )
       FTS( 1 ) = CD( NP + 1 )
       FTS( 2 ) = CD( NP + 4 )
       FTS( 3 ) = CD( NP + 5 )
       FTS( 4 ) = CD( NP + 8  )
       FTD( 1 ) = CD( NP + 3 )
       FTD( 2 ) = -CD( NP + 2 )
       FTD( 3 ) = CD( NP + 7 )
       FTD( 4 ) = -CD( NP + 6 )
    IF( IK. EQ. NGL. AND. ICNTRL. EQ. 2 ) GO TO 450
    GO TO 470
450    FTS( 2 ) = FTS( 2 ) + BETA
       FTD( 2 ) = FTD( 2 ) + RHOC
       FTD( 2 ) = -FTD( 2 )
470 CALL MULT( CTS, FTS, FTP, 4, 4, 1 )
        AXY       = FTP( 1 ) + CCND1
        BXY       = FTP( 2 ) + CCND2
        CXY       = FTP( 3 ) + CCND3
        DXY       = FTP( 4 ) + CCND4
  CALL MULT( CTS, FTD, FTP, 4, 4, 1 )
        AXZ       = FTP( 1 )
        BXZ       = FTP( 2 )
        CXZ       = FTP( 3 )
        DXZ       = FTP( 4 )
        XREF      = ZERO
500 DO 1300 IAZ = 1 , NTIMES
        XREF2     = XREF * XREF
        PHITAP    = PHI * XREF / XLEN
        SPHIT     = DSIN( PHITAP )
        CPHIT     = DCOS( PHITAP )
        DIMEX     = XREF / XLEN
        TANT      = XREF2 * XPH2 / ESTIF
        ALOAD     = W * TANT / TWO
        DEFLXY    = AXY * SPHIT + BXY* CPHIT + CXY * DIMEX+
   *                 DXY + ALOAD
        DEFLXZ    = AXZ * SPHIT + BXZ * CPHIT + CXZ * DIMEX +DXZ
        AMXY      = BMXY( IK ) + SHXY( IK ) * XREF - W *
   *                 XREF2 /TWO - P1( IK ) * ( DEFLXY - DEXY( IK))
        AMXZ      = BMXZ( IK ) - SHXZ( IK ) * XREF +
   *                P1( IK ) * ( DEFLXZ - DEXZ( IK ) )
      IF( ICNTRL. EQ. 2 ) GO TO 900
          AMOMC     = DSQRT( AMXY * AMXY + AMXZ * AMXZ )
       IF( AMOMC . GT. AMAXCY ) GO TO 800
       GO TO 1200
800       AMAXCY    = AMOMC
          XCM       = X( IK ) + XREF
          DEFLC     = DSQRT ( DEFLXY * DEFLXY + DEFLXZ * DEFLXZ )
       GO TO 1200
900       AMOMR     = DSQRT( AMXY * AMXY + AMXZ * AMXZ )
       IF( AMOMR . GT. AMAXRD ) GO TO 1100
       GO TO 1200
1100      AMAXRD    = AMOMR
          XRM       = X( IK ) + XREF
          DEFLR     = DSQRT( DEFLXY * DEFLXY + DEFLXZ* DEFLXZ )
1200 CONTINUE
          XREF1     = X( IK ) + XREF
          XREF      = XREF + XLEN / NTIMES
1300 CONTINUE
          IK        = IK + 1
1500 CONTINUE
      IF( ICNTRL. EQ. 1 ) GO TO 300
          PC        = P1( NODEC )
          PR        = P1( NODER )
     RETURN
     END
```

```
      SUBROUTINE STOPTB
     1          ( TETA , NPHBR, NRDBR, ALTH, ALF, STROK, KTERAT, GC      )
C
C---- >>> SUBROUTINE TO CALCULATE THE REQUIRED LENGTH OF STOP-TUBE
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / GLOFOR / FX(5), FY(5), F1, F2, F3, F4
      COMMON / STOTBS / CL, RL, STPTB
      COMMON / ELEN   / NUMEL,NUMNP, NOCYE, NGL, NGLA
      COMMON /  ORD1  / NODE1( 10), XORD1( 10), NODE2( 10), XORD2(10)
C
      DATA TWO, HUNDRD / 2.0000, 100.0000 /
C
C---- >>> INCREMENT FOR STOP-TUBE LENGTH
C
              GCI     = STROK / HUNDRD
C
C---- >>> CALCULATE TOTAL LATERAL FORCE
C
              TF      = DABS( F1 ) + DABS( F2 ) + DABS( F3 ) + DABS( F4)
          DO 100 I = 1, NPHBR
  100         TF      = TF + DABS( FX(I) )
          DO 110 I = 1, NRDBR
  110         TF      = TF + DABS( FY(I) )
              F       = TF / TWO
C
C---- >>> CHECK TOTAL FORCE AND CROOKEDNESS ANGLE LIMITS
C
          IF ( F .LT. ALF .AND. DABS( TETA ) .LT. ALTH ) RETURN
              GC      = GC + GCI
          IF ( GC - STROK / TWO / TWO ) 120, 120, 900
  120         KTERAT = 2
      RETURN
  900 PRINT 910
  910 FORMAT ( 1H1, ///, 5( 25H* * * * * ERROR * * * * *, / ),
     1        ///, 45HFORCE AND CROOKEDNESS ANGLE LIMITS AT          ,/
     2             45HSLIDING CONNECTION ARE TOO SMALL;              ,/
     3             45HRESULTS IN UNECONOMICAL DESIGN;                ,/
     4             45HSTOP TUBE LENGTH BECOMES > STROKE / 4;         ,/
     5             45HSUGGESTION - INCREASE LIMITING VALUES.         ,/ )
      STOP
      END
```

```
      SUBROUTINE STRESS
     I          ( KEYF, KEYT, KEYP, RIC, CHDS, CPPRE,  FYRODT, FYCYLT,
     I            PINCR1, PINCR2, KEYST, LFLUID, P, BMC, BMR,P1,PC,PR,
     C            HSC, HSR, AXTEN, CSTR, RSTR, CSS, NCSS, NPMAX,
     O           RSS, NRSS                                             )
C
C---- >>> SUBROUTINE TO CHECK THE MAXIMUM STRESSES WITH THE LIMITING
C         STRESSES
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / CRPROP / RDZ, CYZ, RDZI, CYZI, HSCCI, HSCCO, HSCRI,
     *                  HSCRO, BAREAC, BAREAP, CAREAC, CAREAR
      COMMON / WGTVER / WC, WR
      DATA ZERO   / 0.00D00    /
      DATA LYES / 3HYES /
      DIMENSION P1( NPMAX )
C
C
C---- >>> CALCULATE ALL STRESSES
C
C             HOOP STRESSES
C
              PRE     = PC/ BAREAC
              HSC     = HSCCI * PRE
              HSCO    = HSCCO * PRE
              HSR     = ZERO
          IF ( LFLUID .EQ. LYES ) HSR = HSCRI * PRE
              HSRO    = ZERO
          IF ( LFLUID .EQ. LYES ) HSRO = HSCRO * PRE
C
C             LONGITUDINAL STRESSES
C
              AXTEN   = ZERO
          IF ( CHDS .LT. ZERO ) AXTEN = PC / CAREAC
              CSTR    = BMC / CYZ
              CSTRI   = BMC / CYZI
          IF ( LFLUID .EQ. LYES ) PR = PR- PRE * BAREAR
              AXRST   = PR / CAREAR
              RSTR    = BMR / RDZ + AXRST
              RSTRI   = BMR / RDZI + AXRST
C
C             SHEAR STRESSES
C
              CSSO    = HSCO + CSTR
              CSSI    = HSC + CSTRI
          IF ( CSSO .GT. CSSI ) GO TO 20
              CSS     = CSSI
              NCSS    = 2
          GO TO 50
   20         CSS     = CSSO
              NCSS    = 1
   50         RSS     = ZERO
              NRSS    = 0
          IF ( LFLUID .NE. LYES ) GO TO 90
              RSSO    = HSRO + RSTR
              RSSI    = HSR + RSTRI
          IF ( RSSO .GT. RSSI ) GO TO 60
              RSS     = RSSI
```

```
            NRSS    = 2
         GO TO 90
   60       RSS     = RSSO
            NRSS    = 1
   90    CONTINUE
         IF ( KEYF .NE. 1 ) GO TO 500
         IF ( KEYST .NE. 1 ) GO TO 500
C
C---- >>> CHECK WITH LIMITING STRESSES
C
            STRMX1  = DMAX1 ( CSTR, HSC, CSS )
            STRMX2  = DMAX1 ( RSTR, HSR, RSS )
         IF ( STRMX1 .GT. FYCYLT .OR. STRMX2 .GT. FYRODT ) GO TO 100
         IF ( KEYT .EQ. 2 ) GO TO 400
C
C---- >>> CHANGE THE TRIAL LOAD CORRESPONDINGLY
C
            P       = P + PINCR1
      RETURN
  100    IF ( KEYP .EQ. 2 ) GO TO 200
            P       = P - PINCR1 + PINCR2
            KEYT    = 2
      RETURN
C
C---- >>> ITERATIVE REFINEMENT SECTION
C
  200       P       = P - PINCR2
            KEYF    = 2
      RETURN
  400       P       = P + PINCR2
            KEYP    = 2
      RETURN
  500       KEYF    = 3
      RETURN
      END
```

```
C
      SUBROUTINE OUTPUT
     I         ( KWIT, BAREAC, XCY, XRD, YCMAX, YRMAX, CHDS, GC, TETA,
     I           FYCYLT, FYRODT, CSTR, RSTR, HSC, HSR, AXTEN,
     I           NPHBR, NPDBR, THC, CSS, NCSS, RSS, NRSS , P , EXL      )
C---- >>> SUBROUTINE TO PRINT ALL THE RESULTS
C
      IMPLICIT REAL * 8 ( A - H, O - Z )
      COMMON / FSOPTF / OPPRE, ALTH, ALF, FS, LFSTP
      COMMON / GLDFCR / FX(5), FY(5), F1, F2, F3, F4
      COMMON / ID     / IDCARD(40), NPROB, IPROB(19), LPRTP
      COMMON / UNITS  / LNTU, LODU, LPREU, LANGU
C
      DATA ZERO, TWO, H180 / 0.0D00, 2.0D00, 180.0D00 /
      DATA PI / 3.14159265358979300C0 /
      DATA LDEG   / 4HDEG      /
C
C---- >>> FORMATS
C
  100 FORMAT ( 1H1, 5X, 36HPROGRAM SACFI  - STRESS ANALYSIS OF ,
     1           21HCYLINDERS ( REGULAR ), //, 2( 5X, 20A4, / ), /      )
  110 FORMAT ( 5X, 8HPROBLEM , A4, //, 1X, 19A4                        )
  120 FORMAT ( //, 5X,35HRESULTS:      CRITICAL LOAD ANALYSIS, /       )
  130 FORMAT ( //, 5X,44HRESULTS:      ANALYSIS FOR A GIVEN OPERATING ,
     1                     8HPRESSURE, /                                )
  140 FORMAT ( //, 5X,45HRESULTS:      ANALYSIS TO DETERMINE STOP-TUBE ,
     1                     6HLENGTH, /                                  )
  150 FORMAT (  /,14X,25HCRITICAL LOAD             = ,1PD10.3, 4X, A4,
     1           //,14X,25HMAXIMUM FLUID PRESSURE = ,1PD10.3, 4X, A4,
     2           //,14X,25HCROOKEDNESS ANGLE       = ,1PD12.5, 2X, A4, /  )
  160 FORMAT (  /,14X,25HOPERATING PRESSURE       = ,1PD10.3, 4X, A4,
     1           //,14X,25HLOAD                    = ,1PD10.3, 4X, A4,
     2           //,14X,25HCROOKEDNESS ANGLE       = ,1PD12.5, 2X, A4, /  )
  180 FORMAT (  /, 5X,34HREQUIRED LENGTH OF STOP-TUBE     = 1PD10.3,4X,A4
     1           //, 5X,34HCORRESPONDING EXTENDED LENGTH   = 1PD10.3,4X,A4
     2           //, 5X,32HRESULTS WITH THIS STOP-TUBE ARE:, /          )
  250 FORMAT ( 1H1, /, 5X,40HANALYSIS AFTER APPLYING GIVEN FACTOR OF ,
     1                  10HSAFETY OF , F6.3, 2X, 2HON, 2X, A4, 2H: , /   )
  260 FORMAT (  /,14X,25HLOAD                    = ,1PD10.3, 4X, A4,
     1           //,14X,25HFLUID PRESSURE          = ,1PD10.3, 4X, A4,
     2           //,14X,25HCROOKEDNESS ANGLE       = ,1PD12.5, 2X, A4, /  )
  300 FORMAT (  /, 5X, 9HCYLINDER:,
     1           //,10X,29HMAXIMUM DEFLECTION           = ,1PD10.3, 4X, A4,
     2           //,10X,29HMAXIMUM LONGITUDINAL STRESS= ,1PD10.3, 4X, A4,
     3           //,10X,29HAT A DISTANCE FROM CYL SUP = ,1PD10.3, 4X, A4,
     4           //,10X,29HFACTOR OF SAFETY ON CYL    = ,1PD10.3, /      )
  312 FORMAT (  /,10X,29HMAX SHEAR STRESS IN CYL    = ,1PD10.3, 4X, A4,
     1           /,10X,24HAT MAX LONG STRESS POINT                       )
  314 FORMAT ( 10X, 21HAND AT OUTER SURFACE                              )
  316 FORMAT ( 10X, 21HAND AT INNER SURFACE                              )
  318 FORMAT (  /,10X,29HFACTOR OF SAFETY ON CYL    = ,1PD10.3, /      )
  320 FORMAT (  /,10X,29HMAXIMUM HOOP STRESS IN CYL = ,1PD10.3, 4X, A4,
     1           //,10X,29HFACTOR OF SAFETY ON CYL    = ,1PD10.3, /      )
  325 FORMAT (  /,10X,29HAXIAL TENSION IN OVER HANG = ,1PD10.3, 4X, A4,
     1           //,10X,29HFACTOR OF SAFETY ON CYL    = ,1PD10.3,
     2           //,10X,29HEND DEFLECTION IN OVERHANG = ,1PD10.3, 4X, A4 )
  330 FORMAT (  /, 5X, 9HROD      :,
     1           //,10X,29HMAXIMUM DEFLECTION           = ,1PD10.3, 4X, A4,
```

```
    2          //,10X,29HMAXIMUM LONGITUDINAL STRESS= ,1PD10.3, 4X, A4,
    3          //,10X,29HAT A DISTANCE FROM CYL SUP = ,1PD10.3, 4X, A4,
    4          //,10X,29HFACTOR OF SAFETY ON ROD    = ,1PD10.3, /       )
  342 FORMAT (  /,10X,29HMAX SHEAR STRESS IN ROD    = ,1PD10.3, 4X, A4,
    1           /,10X,24HAT MAX LONG STRESS POINT                       )
  348 FORMAT (  /,10X,29HFACTOR OF SAFETY ON ROD    = ,1PD10.3, /       )
  350 FORMAT (  /,10X,29HMAXIMUM HOOP STRESS IN ROD = ,1PD10.3, 4X, A4,
    1          //,10X,29HFACTOR OF SAFETY ON ROD    = ,1PD10.3, /       )
  360 FORMAT ( 1H1, //, 5X, 29HFORCES AT SLIDING CONNECTION:, //, 15X,
    1          23HPISTON BEARINGS (SEALS), 6X, 5HFORCE, /,25X, 2HNO, / )
  370 FORMAT ( /, 5( 25X, I2, 12X, 1PD10.3, 2X, A4, // )                )
  380 FORMAT ( /,18X, 20HROD BEARINGS (SEALS), 6X, 5HFORCE,/,25X, 2HNO/)
  390 FORMAT ( //8X38HF1- FORCE AT PISTON HEAD FRONT FACE  =1PD11.3,2XA4
    1          //8X38HF2- FORCE AT STUFFING BOX FRONT FACE =1PD11.3,2XA4
    2          //8X38HF3- FORCE AT PISTON HEAD BACK FACE   =1PD11.3,2XA4
    3          //8X38HF4- FORCE AT STUFFING BOX INNER FACE =1PD11.3,2XA4
    4           /,11X,33H(ZERO FORCES INDICATE NO CONTACT) , /          )
  400 FORMAT ( ///, 10X, 39HTHETA EQUAL TO ZERO IMPLIES CONTINUOUS  ,
    1          17HCONTACT AT GLAND.  , /, 10X,
    2          34HABOVE FORCES CANNOT BE CALCULATED.
    3          33HHENCE, ARE PRINTED OUT AS ZERO'S.  ,  //              )
C
               TEMP   = H180 / PI
         IF ( LANGU .EQ. LDEG ) TETA = TETA * TEMP
               PRE    = P / BAREAC
         IF ( KWIT .NE. 1 ) GO TO 540
C
C---- >>> PRINT ALL RESULTS
C
      PRINT 100, ( IDCARD(I), I = 1, 40 )
      PRINT 110, NPROB, ( IPROB(I), I = 1, 19 )
         GO TO ( 510, 520, 530 ), LPRTP
  510 PRINT 120
      PRINT 150, P, LODU, PRE, LPREU, TETA, LANGU
         GO TO 550
  520 PRINT 130
      PRINT 160, OPPRE, LPREU, P, LODU, TETA, LANGU
         GO TO 550
  530 PRINT 140
      PRINT 180, GC, LNTU, FXL, LNTU
      PRINT 150, P, LODU, OPPRE, LPPEU, TETA, LANGU
         GO TO 550
  540 PRINT 250, FS, LFSTP
      PRINT 260, P, LODU, PRE, LPREU, TETA, LANGU
C
C---- >>> CALCULATE THE FACTOR OF SAFETY'S ON MAXIMUM STRESSES WITH
C        LIMITING STRESSES AND PRINT
C
  550          FCSF   = FYCYLT / CSTR
      PRINT 300, YCMAX, LNTU, CSTR, LPPEU, XCY, LNTU, FCSF
               FCSF   = FYCYLT / CSS
               CSS    = CSS / TWO
      PRINT 312, CSS, LPPEU
         IF ( NCSS .EQ. 1 ) PRINT 314
         IF ( NCSS .EQ. 2 ) PRINT 316
      PRINT 318, FCSF
               FCSF   = FYCYLT / HSC
      PRINT 320, HSC, LPPEU, FCSF
         IF ( CHOS .GE. ZERO ) GO TO 560
               FCSF   = FYCYLT / AXTEN
               ENDDF  = THC * CHOS
      PRINT 325, AXTEN, LPREU, FCSF, ENDDF, LNTU
  560          FCSF   = FYRODT / RSTR
      PRINT 330, YRMAX, LNTU, RSTR, LPREU, XRC, LNTU, FCSF
         IF ( HSR .EQ. ZERO ) GO TO 570
               FCSF   = FYRODT / RSS
               RSS    = RSS / TWO
      PRINT 342, RSS, LPREU
         IF ( NRSS .EQ. 1 ) PRINT 314
         IF ( NRSS .EQ. 2 ) PRINT 316
      PRINT 348, FCSF
               FCSF   = FYRODT / HSR
      PRINT 350, HSR, LPREU, FCSF
  570 PRINT 360
      PRINT 370, ( I, FX(I), LODU, I = 1, NPHBR )
      PRINT 380
      PRINT 370, ( I, FY(I), LODU, I = 1, NRCBR )
      PRINT 390, F1, LODU, F2, LODU, F3, LODU, F4, LODU
         IF ( TETA .EQ. ZERO ) PRINT 400
      RETURN
      END
```

PROGRAM SACFI - STRESS ANALYSIS OF HYDRAULIC CYLINDERS.

N. RAVI SHANKAR   EXAMPLE PROBLEMS
CODED ON NOVEMBER 1 1978

PROBLEM 1

SOLID ROD , HORIZONTAL CYLINDER, CRITICAL LOAD ANALYSIS

INPUT DATA:

TABLE 1: CONTROL DATA

PROBLEM TYPE = 1 - CRITICAL LOAD ANALYSIS & ANALYSIS FOR A FACTORED LOAD

TABLES RETAINED FROM PREVIOUS PROBLEM

2 3 4 5 6 7

NO KEEP OPTIONS EXERCISED

TABLE 2: UNITS OF MEASUREMENT

LENGTH	LOAD	PRESSURE	ANGULAR
INCH	KIPS	KSI	RAD

TABLE 3: CYLINDER DIMENSIONS

LENGTHS:

STROKE	PISTON HEAD	STUFFING BOX	END PLATE	HINGE DIST.
5.000000D+01	1.780000D+00	5.625000D-01	9.000000D-01	0.0

CYLINDER	ROD	EXTENDED	STOP TUBE
5.290600D+01	5.278370D+01	1.056890D+02	0.0

DIAMETERS:

CYL. OUTER	CYL. INNER	ROD OUTER	ROD INNER	
3.500000D+00	3.070000D+00	2.000000D+00	0.0	SOLID ROD

CYL. PIN *	ROD PIN *	PISTON HEAD @	STUF. BOX @
5.000000D-03	5.000000D-03	2.995000D+00	2.052000D+00

(* ZERO, THE END IS FIXED) (@ ZERO, OTHER OPTION IS INPUT)

CLEARANCES BETWEEN:

CYLINDER AND STUFFING BOX	CYLINDER AND PISTON HEAD @	ROD AND STUF. BOX @
0.0	0.0	0.0

(@ ZERO, OTHER OPTION IS INPUT)

TABLE 4: BEARINGS AND SEALS

PISTON BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FROM BACK FACE
5.300000D-01	3.725000D-01	1.500000D+04	0.0	1.515000D+00
1.000000D+00	3.815000D-01	4.000000D+02	0.0	7.500000D-01

ROD BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FROM BACK FACE
1.000000D+00	1.250000D-01	1.500000D+04	0.0	1.062000D+00

(A IS USED TO CALCULATE B - HENCE, EITHER A OR B IS INPUT
ZERO'S ABOVE INDICATE THAT THEY ARE NOT INPUT)

TABLE 5: WEIGHTS AND MATERIAL PROPERTIES

WEIGHTS OF PARTS:

CYLINDER	ROD (PER UNIT LENGTH)	PISTON HEAD	STUFFING BOX
2.400000D-03	3.000000D-03	4.157000D-03	1.777000D-02

MATERIAL PROPERTIES:

YOUNGS MODULUS CYLINDER	YOUNGS MODULUS ROD	YIELD STRESS CYLINDER	YIELD STRESS ROD
2.900000D+04	2.900000D+04	7.500000D+01	4.050000D+01

TABLE 6: INCLINATION,FRICTION COEFFICIENT,FACTOR OF SAFTEY,

CYLINDER INCLINATION 0.0
FRICTION COEFFICIENTS
CYLINDER END 0.0
ROD END 0.0

TABLE7: STATION DATA
AUTOOPTION

NUMBER OF ELEMENTS

CYLINDER	3
ROD	1

TABLE8: FIXITY CONDITIONS,ECCENTRICITY OF LOADING

NODE	FIXITY ALONG PLANE XY	FIXITY ALONG PLANE XZ	ECCENTRICITY ALONG XY	ECCENTRICITY ALONG XZ	MOMENTS ABOUT Y	MOMENTS ABOUT Z
1	PIN	PIN	0.0	0.0	0.0	0.0
5	PIN	PIN	0.0	0.0	0.0	0.0

AXIAL LOAD DISTRIBUTION IS UNIFORM.

FACTOR OF SAFETY = 1.000 ON LOAD

PROGRAM SACFI - STRESS ANALYSIS OF CYLINDERS (REGULAR)

N. RAVI SHANKAR EXAMPLE PROBLEMS
CODED ON NOVEMBER 1 1978

PROBLEM 1

SOLID ROD , HORIZONTAL CYLINDER, CRITICAL LOAD ANALYSIS

RESULTS: CRITICAL LOAD ANALYSIS

CRITICAL LOAD	=	2.582D+01	KIPS
MAXIMUM FLUID PRESSURE	=	3.605D+00	KSI
CROOKEDNESS ANGLE	=	3.45558D-05	RAD

CYLINDER:

MAXIMUM DEFLECTION	=	7.846D-01	INCH
MAXIMUM LONGITUDINAL STRESS	=	1.319D+01	KSI
AT A DISTANCE FROM CYL SUP	=	5.375D+01	INCH
FACTOR OF SAFETY ON CYL	=	5.687D+00	
MAX SHEAR STRESS IN CYL AT MAX LONG STRESS POINT AND AT INNER SURFACE	=	1.800D+01	KSI
FACTOR OF SAFETY ON CYL	=	2.084D+00	
MAXIMUM HOOP STRESS IN CYL	=	2.461D+01	KSI
FACTOR OF SAFETY ON CYL	=	3.047D+00	

ROD :

MAXIMUM DEFLECTION	=	8.208D-01	INCH
MAXIMUM LONGITUDINAL STRESS	=	4.046D+01	KSI
AT A DISTANCE FROM CYL SUP	=	5.948D+01	INCH
FACTOR OF SAFETY ON ROD	=	1.001D+00	

FORCES AT SLIDING CONNECTION:

PISTON BEARINGS (SEALS) NO	FORCE	
1	6.452D+00	KIPS
2	2.333D-01	KIPS

ROD BEARINGS (SEALS) NO	FORCE	
1	6.685D+00	KIPS

F1- FORCE AT PISTON HEAD FRONT FACE = 0.0 KIPS

F2- FORCE AT STUFFING BOX FRONT FACE = 0.0 KIPS

F3- FORCE AT PISTON HEAD BACK FACE = 0.0 KIPS

F4- FORCE AT STUFFING BOX INNER FACE = 0.0 KIPS
(ZERO FORCES INDICATE NO CONTACT)

PROGRAM SACFI - STRESS ANALYSIS OF HYDRAULIC CYLINDERS.

N. RAVI SHANKAR   EXAMPLE PROBLEMS
CODED ON NOVEMBER 1 1978

PROBLEM   2

HOLLOW ROD,VERTICAL CYLINDER,ECCENTRICITY ALONG X AND Y AXES

INPUT DATA:

TABLE 1:   CONTROL DATA

PROBLEM TYPE = 1 - CRITICAL LOAD ANALYSIS & ANALYSIS FOR A FACTORED LOAD

TABLES RETAINED FROM PREVIOUS PROBLEM

2	3	4	5	6	7
KEEP		KEEP	KEEP		KEEP

TABLE 2:   UNITS OF MEASUREMENT

LENGTH	LOAD	PRESSURE	ANGULAR
INCH	KIPS	KSI	RAD

TABLE 3:   CYLINDER DIMENSIONS

LENGTHS:

STROKE	PISTON HEAD	STUFFING BOX	END PLATE	HINGE DIST.
5.00000D+01	1.78000D+00	5.62500D-01	9.00000D-01	0.0

CYLINDER	ROD	EXTENDED	STOP TUBE
5.29060D+01	5.27830D+01	1.05689D+02	0.0

DIAMETERS:

CYL. OUTER	CYL. INNER	ROD OUTER	ROD INNER	
3.50000D+00	3.02000D+00	2.03000D+00	1.50000D+00	HOLLOW ROD WITH FLUID

CYL. PIN *	ROD PIN *	PISTON HEAD @	STUF. BOX @
5.00000D-01	5.00000D-01	2.99500D+00	2.05200D+00

(* ZERO, THE END IS FIXED) (@ ZERO, OTHER OPTION IS INPUT)

CLEARANCES BETWEEN:

CYLINDER AND STUFFING BOX	CYLINDER AND PISTON HEAD @	ROD AND STUF. BOX @
0.0	0.0	0.0

(@ ZERO, OTHER OPTION IS INPUT)

TABLE 4:   BEARINGS AND SEALS

PISTON BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FROM BACK FACE
5.30000D-01	3.72500D-01	1.50000D+04	0.0	1.51500D+00
1.00000D+00	3.81500D-01	4.00000D+02	0.0	7.50000D-01

ROD BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FROM BACK FACE
1.00000D+00	1.25000D-01	1.50000D+04	0.0	1.06200D+00

(A IS USED TO CALCULATE B - HENCE, EITHER A OR B IS INPUT
ZERO'S ABOVE INDICATE THAT THEY ARE NOT INPUT)

TABLE 5:   WEIGHTS AND MATERIAL PROPERTIES

WEIGHTS OF PARTS:

CYLINDER	ROD (PER UNIT LENGTH)	PISTON HEAD	STUFFING BOX
2.40000D-03	3.00000D-03	4.15700D-03	1.77700D-02

MATERIAL PROPERTIES:

YOUNGS MODULUS CYLINDER	YOUNGS MODULUS ROD	YIELD STRESS CYLINDER	YIELD STRESS ROD
2.90000D+04	2.90000D+04	7.50000D+01	4.05000D+01

TABLE6: INCLINATION,FRICTION COEFFICIENT,FACTOR OF SAFTEY,
CYLINDER INCLINATION   1.5070+00
FRICTION COEFFICIENTS
CYLINDER END   0.0
ROD END   0.0

TABLE7: STATION DATA
AUTOOPTION

NUMBER OF ELEMENTS
CYLINDER 3
ROD 1

TABLE8: FIXITY CONDITIONS,ECCENTRICITY OF LOADING

NODE	FIXITY ALONG PLANE XY	XZ	ECCENTRICITY ALONG XY	XZ	MOMENTS ABOUT Y	Z
1	FIX	PIN	0.0	0.0	0.0	0.0
5	PIN	PIN	5.0000D-01	5.0000D-01	0.0	0.0

AXIAL LOAD DISTRIBUTION IS UNIFORM

FACTOR OF SAFETY = 1.000 ON LOAD

PROGRAM SACFI - STRESS ANALYSIS OF CYLINDERS (REGULAR)

N. RAVI SHASKAR EXAMPLE PROBLEMS
CODED ON NOVEMBER 1 1978

PROBLEM 2

HOLLOW ROD,VERTICAL CYLINDER,ECCENTRICITY ALONG X AND Y AXES

RESULTS: CRITICAL LOAD ANALYSIS

CRITICAL LOAD = 1.403D+01 KIPS

MAXIMUM FLUID PRESSURE = 1.959D+00 KSI

CROOKEDNESS ANGLE = 1.79873D-05 RAD

CYLINDER:

MAXIMUM DEFLECTION = 6.607D-01 INCH

MAXIMUM LONGITUDINAL STRESS= 6.782D+00 KSI

AT A DISTANCE FROM CYL SUP = 5.375D+01 INCH

FACTOR OF SAFETY ON CYL = 1.106D+01

MAX SHEAR STRESS IN CYL = 9.614D+00 KSI
AT MAX LONG STRESS POINT
AND AT INNER SURFACE

FACTOR OF SAFETY ON CYL = 3.900D+00

MAXIMUM HOOP STRESS IN CYL = 1.338D+01 KSI

FACTOR OF SAFETY ON CYL = 5.607D+00

ROD :

MAXIMUM DEFLECTION = 6.948D-01 INCH

MAXIMUM LONGITUDINAL STRESS= 3.544D+01 KSI

AT A DISTANCE FROM CYL SUP = 7.310D+01 INCH

FACTOR OF SAFETY ON ROD = 1.143D+00

MAX SHEAR STRESS IN ROD = 2.024D+01 KSI
AT MAX LONG STRESS POINT
AND AT OUTER SURFACE

FACTOR OF SAFETY ON ROD = 1.001D+00

MAXIMUM HOOP STRESS IN ROD = 6.956D+00 KSI

FACTOR OF SAFETY ON ROD = 5.789D+00

FORCES AT SLIDING CONNECTION:

PISTON BEARINGS (SEALS) NO	FORCE	
1	3.359D+00	KIPS
2	1.214D-01	KIPS

ROD BEARINGS (SEALS) NO	FORCE	
1	3.480D+00	KIPS

F1- FORCE AT PISTON HEAD FRONT FACE = 0.0 KIPS

F2- FORCE AT STUFFING BOX FRONT FACE = 0.0 KIPS

F3- FORCE AT PISTON HEAD BACK FACE = 0.0 KIPS

F4- FORCE AT STUFFING BOX INNER FACE = 0.0 KIPS
(ZERO FORCES INDICATE NO CONTACT)

PROGRAM SACFI - STRESS ANALYSIS OF HYDRAULIC CYLINDERS.

N. RAVI SHANKAR   EXAMPLE PROBLEMS
CODED ON NOVEMBER 1 1978

PROBLEM 3

HOLLOW ROD ,INCLINED AT 30, ECCENTRICITY AT INTERIOR NODE

INPUT DATA:

TABLE 1: CONTROL DATA

PROBLEM TYPE = 1 - CRITICAL LOAD ANALYSIS & ANALYSIS FOR A FACTORED LOAD

TABLES RETAINED FROM PREVIOUS PROBLEM

2	3	4	5	6	7
	KEEP	KEEP	KEEP		KEEP

TABLE 2: UNITS OF MEASUREMENT

LENGTH	LOAD	PRESSURE	ANGULAR
INCH	KIPS	KSI	DEG

TABLE 3: CYLINDER DIMENSIONS

LENGTHS:

STROKE	PISTON HEAD	STUFFING BOX	END PLATE	HINGE DIST.
5.000000+01	1.780000+00	5.625000-01	9.000000-01	0.0

CYLINDER	ROD	EXTENDED	STOP TUBE
5.290600+01	5.278300+01	1.05689D+02	0.0

DIAMETERS:

CYL. OUTER	CYL. INNER	ROD OUTER	ROD INNER	
3.500000+00	3.020000+00	2.000000+00	1.500000+00	HOLLOW ROD WITH FLUID

CYL. PIN *	ROD PIN *	PISTON HEAD @	STUF. BOX @
5.000000-01	5.000000-01	2.995000+00	2.052000+00

(* ZERO, THE END IS FIXED) (@ ZERO, OTHER OPTION IS INPUT)

CLEARANCES BETWEEN:

CYLINDER AND STUFFING BOX	CYLINDER AND PISTON HEAD @	ROD AND STUF. BOX @
0.0	0.0	0.0

(@ ZERO, OTHER OPTION IS INPUT)

TABLE 4: BEARINGS AND SEALS

PISTON BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FROM BACK FACE
5.300000-01	3.725000-01	1.500000+04	0.0	1.515000+00
1.000000+00	3.815000-01	4.000000+02	0.0	7.500000-01

ROD BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FROM BACK FACE
1.000000+00	1.250000-01	1.500000+04	0.0	1.062000+00

(A IS USED TO CALCULATE B - HENCE, EITHER A OR B IS INPUT
ZERO'S ABOVE INDICATE THAT THEY ARE NOT INPUT)

TABLE 5: WEIGHTS AND MATERIAL PROPERTIES

WEIGHTS OF PARTS:

CYLINDER	ROD (PER UNIT LENGTH)	PISTON HEAD	STUFFING BOX
2.400000-03	3.000000-03	4.157000-03	1.777000-02

MATERIAL PROPERTIES:

YOUNGS MODULUS CYLINDER	YOUNGS MODULUS ROD	YIELD STRESS CYLINDER	YIELD STRESS ROD
2.900000+04	2.900000+04	7.500000+01	4.050000+01

TABLE6: INCLINATION,FRICTION COEFFICIENT,FACTOR OF SAFTEY,

CYLINDER INCLINATION	3.0000+01
FRICTION COEFFICIENTS	
CYLINDER END	1.0000-03
ROD END	1.0000-03

TABLE7: STATION DATA
AUTOOPTION

NUMBER OF ELEMENTS

	CYLINDER	3
	ROD	1

TABLE8: FIXITY CONDITIONS,ECCENTRICITY OF LOADING

NODE	FIXITY ALONG PLANE XY	FIXITY ALONG PLANE XZ	ECCENTRICITY ALONG XY	ECCENTRICITY ALONG XZ	MOMENTS ABOUT Y	MOMENTS ABOUT Z
1	PIN	PIN	0.0	0.0	0.0	0.0
3			5.0000D-01	0.0	0.0	0.0
5	PIN	PIN	1.0000D+00	0.0	0.0	0.0

AXIAL LOAD DISTRIBUTION IS UNIFORM

FACTOR OF SAFETY = 1.000 ON STRS

PROGRAM SACFI - STRESS ANALYSIS OF CYLINDERS (REGULAR)

N. RAVI SHANKAR EXAMPLE PROBLEMS
CODED ON NOVEMBER 1 1978

PROBLEM 3

HOLLOW ROD ,INCLINED AT 30, ECCENTRICITY AT INTERIOR NODE

RESULTS: CRITICAL LOAD ANALYSIS

CRITICAL LOAD = 1.0030D+01 KIPS

MAXIMUM FLUID PRESSURE = 1.4900D+00 KSI

CROOKEDNESS ANGLE = 1.350210-03 DEG

CYLINDER:

MAXIMUM DEFLECTION = 7.8610-01 INCH

MAXIMUM LONGITUDINAL STRESS= 1.034D+01 KSI

AT A DISTANCE FROM CYL SUP = 5.375D+01 INCH

FACTOR OF SAFETY ON CYL = 7.254D+00

MAX SHEAR STRESS IN CYL = 9.250D+00 KSI
AT MAX LONG STRESS POINT
AND AT OUTER SURFACE

FACTOR OF SAFETY ON CYL = 4.054D+00

MAXIMUM HOOP STRESS IN CYL = 9.560D+00 KSI

FACTOR OF SAFETY ON CYL = 7.845D+00

ROD :

MAXIMUM DEFLECTION = 7.864D-01 INCH

MAXIMUM LONGITUDINAL STRESS= 3.684D+01 KSI

AT A DISTANCE FROM CYL SUP = 5.434D+01 INCH

FACTOR OF SAFETY ON ROD = 1.099D+00

MAX SHEAR STRESS IN ROD = 2.022D+01 KSI
AT MAX LONG STRESS POINT
AND AT OUTER SURFACE

FACTOR OF SAFETY ON ROD = 1.001D+00

MAXIMUM HOOP STRESS IN ROD = 5.000D+00 KSI

FACTOR OF SAFETY ON ROD = 8.100D+00

FORCES AT SLIDING CONNECTION:

PISTON BEARINGS (SEALS) NO	FORCE	
1	4.400D+00	KIPS
2	1.591D-01	KIPS

ROD BEARINGS (SEALS) NO	FORCE	
1	4.559D+00	KIPS

F1- FORCE AT PISTON HEAD FRONT FACE = 0.0 KIPS

F2- FORCE AT STUFFING BOX FRONT FACE = 0.0 KIPS

F3- FORCE AT PISTON HEAD BACK FACE = 0.0 KIPS

F4- FORCE AT STUFFING BOX INNER FACE = 0.0 KIPS
(ZERO FORCES INDICATE NO CONTACT)

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PROGRAM SACFI - STRESS ANALYSIS OF HYDRAULIC CYLINDERS.

          N. RAVI SHANKAR          EXAMPLE PROBLEMS
            CODED ON NOVEMBER 1 1978

PROBLEM    4

    ANALYSIS FOR CRITICAL PRESSURE=2KSI, SELF OPTION

INPUT DATA:

TABLE 1:     CONTROL DATA

     PROBLEM TYPE = 2 - ANALYSIS FOR A PARTICULAR PRESSURE

             TABLES RETAINED FROM PREVIOUS PROBLEM

                2     3     4     5     6     7
                           KEEP  KEEP

TABLE 2:     UNITS OF MEASUREMENT

            LENGTH      LOAD      PRESSURE    ANGULAR

             INCH       KIPS        KSI         RAD

TABLE 3:     CYLINDER DIMENSIONS

     LENGTHS:

              STROKE       PISTON HEAD   STUFFING BOX    END PLATE     HINGE DIST.

           5.00000D+01   1.78000D+00   5.62500D-01   9.00000D-01   0.0

             CYLINDER          ROD          EXTENDED      STOP TUBE

           5.29060D+01   5.27830D+01   1.05689D+02   0.0

     DIAMETERS:

            CYL. OUTER    CYL. INNER     ROD OUTER     ROD INNER

           3.50000D+00   3.02000D+00   2.00000D+00   0.0            SOLID ROD

             CYL. PIN *     ROD PIN *    PISTON HEAD @  STUF. BOX @

           5.00000D-01   5.00000D-01   2.99500D+00   2.05200D+00
          (* ZERO, THE END IS FIXED) (@ ZERO, OTHER OPTION IS INPUT)

     CLEARANCES BETWEEN:

             CYLINDER       CYLINDER          ROD
               AND            AND             AND
           STUFFING BOX   PISTON HEAD @   STUF. BOX @

             0.0             0.0             0.0
                        (@ ZERO, OTHER OPTION IS INPUT)

TABLE 4:       BEARINGS AND SEALS

     PISTON BEARINGS:

                 A              A               A              B          DISTANCE FROM
               WIDTH        THICKNESS     YOUNGS MODULUS    STIFFNESS       BACK FACE

           5.30000D-01   3.72500D-01   1.50000D+04   0.0             1.51500D+00
           1.00000D+00   3.81500D-01   4.00000D+02   0.0             7.50000D-01

     ROD BEARINGS:

                 A              A               A              B          DISTANCE FROM
               WIDTH        THICKNESS     YOUNGS MODULUS    STIFFNESS       BACK FACE

           1.00000D+00   1.25000D-01   1.50000D+04   0.0             1.06200D+00

          (A IS USED TO CALCULATE B - HENCE, EITHER A OR  B IS INPUT
                     ZERO'S ABOVE INDICATE THAT THEY ARE NOT INPUT)

TABLE 5:      WEIGHTS AND MATERIAL PROPERTIES

     WEIGHTS OF PARTS:

             CYLINDER          ROD         PISTON HEAD   STUFFING BOX
                (PER UNIT LENGTH)

           2.40000D-03   3.00000D-03   4.15700D-03   1.77700D-02

     MATERIAL PROPERTIES:

               YOUNGS MODULUS                YIELD STRESS
             CYLINDER         ROD          CYLINDER         ROD

           2.90000D+04   2.90000D+04   7.50000D+01   4.05000D+01

TABLE6: INCLINATION,FRICTION COEFFICIENT,FACTOR OF SAFTEY,
     CYLINDER INCLINATION       0.0
     FRICTION COEFFICIENTS
              CYLINDER END      0.0
                   ROD END      0.0
```

TABLE7: STATION DATA
SELFOPTION

NUMBER OF ELEMENTS
CYLINDER 3
ROD 1

STA	X-COORD	STA	X-COORD	NSEG
1	0.0	0	0.0	
2	5.0900D+01	0	0.0	
3	5.2070D+01	0	0.0	
4	5.3240D+01	0	0.0	
5	1.0570D+02	0	0.0	

TABLE8: FIXITY CONDITIONS,ECCENTRICITY OF LOADING

NODE	FIXITY ALONG PLANE		ECCENTRICITY ALONG		MOMENTS ABOUT	
	XY	XZ	XY	XZ	Y	Z
1	PIN	PIN	0.0	0.0	0.0	0.0
5	PIN	PIN	0.0	0.0	0.0	0.0

AXIAL LOAD DISTRIBUTION IS UNIFORM

OPERATING PRESSURE = 2.000000D+00

PROGRAM SACEI - STRESS ANALYSIS OF CYLINDERS (REGULAR)

N. RAVI SHANKAR EXAMPLE PROBLEMS
CODED ON NOVEMBER 1 1978

PROBLEM 4

ANALYSIS FOR CRITICAL PRESSURE=2KSI, SELF OPTION

RESULTS: ANALYSIS FOR A GIVEN OPERATING PRESSURE

OPERATING PRESSURE = 2.0000D+00 KSI

LOAD = 1.4330D+01 KIPS

CROOKEDNESS ANGLE = 1.088470D-05 RAD

CYLINDER:

MAXIMUM DEFLECTION = 2.4300D-01 INCH

MAXIMUM LONGITUDINAL STRESS= 4.2510D+00 KSI

AT A DISTANCE FROM CYL SUP = 5.3750D+01 INCH

FACTOR OF SAFETY ON CYL = 1.7640D+01

MAX SHEAR STRESS IN CYL = 8.6620D+00 KSI
AT MAX LONG STRESS POINT
AND AT INNER SURFACE

FACTOR OF SAFETY ON CYL = 4.3250D+00

MAXIMUM HOOP STRESS IN CYL = 1.3660D+01 KSI

FACTOR OF SAFETY ON CYL = 5.4520D+00

ROD :

MAXIMUM DEFLECTION = 2.4470D-01 INCH

MAXIMUM LONGITUDINAL STRESS= 1.4860D+01 KSI

AT A DISTANCE FROM CYL SUP = 5.4370D+01 INCH

FACTOR OF SAFETY ON ROD = 2.7250D+00

FORCES AT SLIDING CONNECTION:

PISTON BEARINGS (SEALS) NO	FORCE
1	2.032D+00 KIPS
2	7.348D-02 KIPS

ROD BEARINGS (SEALS) NO	FORCE
1	2.106D+00 KIPS

F1- FORCE AT PISTON HEAD FRONT FACE = 0.0 KIPS

F2- FORCE AT STUFFING BOX FRONT FACE = 0.0 KIPS

F3- FORCE AT PISTON HEAD BACK FACE = 0.0 KIPS

F4- FORCE AT STUFFING BOX INNER FACE = 0.0 KIPS
(ZERO FORCES INDICATE NO CONTACT)

PROGRAM SACFI - STRESS ANALYSIS OF HYDRAULIC CYLINDERS.

N. RAVI SHANKAR EXAMPLE PROBLEMS
CODED ON NOVEMBER 1 1978

PROBLEM 5

ANALYSIS FOR DETERMINATION OF STOP TUBE LENGTH METRIC UNITS

INPUT DATA:

TABLE 1: CONTROL DATA

PROBLEM TYPE = 3 - ANALYSIS TO DETERMINE SUITABLE STOP-TUBE LENGTH

TABLES RETAINED FROM PREVIOUS PROBLEM

2 3 4 5 6 7

NO KEEP OPTIONS EXERCISED

TABLE 2: UNITS OF MEASUREMENT

LENGTH	LOAD	PRESSURE	ANGULAR
CM	KGS	KGSC	RAD

TABLE 3: CYLINDER DIMENSIONS

LENGTHS:

STROKE	PISTON HEAD	STUFFING BOX	END PLATE	HINGE DIST
1.27000D+02	4.50000D+00	1.42875D+00	2.28600D+00	0.0

CYLINDER ROD EXTENDED STOP TUBE

THESE NOT INPUT BECAUSE STOP TUBE LENGTH ANALYSIS IS ASKED

DIAMETERS:

CYL. OUTER	CYL. INNER	ROD OUTER	ROD INNER	
8.89000D+00	7.67000D+00	5.00000D+00	0.0	SOLID ROD

CYL. PIN *	ROD PIN *	PISTON HEAD @	STUF. BOX @
1.27000D+00	1.27000D+00	7.60730D+00	5.21208D+00

(* ZERO, THE END IS FIXED) (@ ZERO, OTHER OPTION IS INPUT)

CLEARANCES BETWEEN:

CYLINDER AND STUFFING BOX	CYLINDER AND PISTON HEAD @	ROD AND STUF. BOX @
0.0	0.0	0.0

(@ ZERO, OTHER OPTION IS INPUT)

TABLE 4: BEARINGS AND SEALS

PISTON BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FRO BACK FACE
1.34620D+00	9.50000D-01	1.00000D+06	0.0	3.85000D+00
2.50000D+00	9.50000D-01	2.82000D+04	0.0	1.90000D+00

ROD BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FRO BACK FACE
2.50000D+00	3.00000D-01	1.00000D+06	0.0	2.70000D+00

(A IS USED TO CALCULATE B - HENCE, EITHER A OR B IS INPUT
ZERO'S ABOVE INDICATE THAT THEY ARE NOT INPUT)

TABLE 5: WEIGHTS AND MATERIAL PROPERTIES

WEIGHTS OF PARTS:

CYLINDER	ROD (PER UNIT LENGTH)	PISTON HEAD	STUFFING BOX
2.12500D+00	1.40000D+00	1.95000D+00	8.30000D+00

MATERIAL PROPERTIES:

YOUNGS MODULUS CYLINDER	YOUNGS MODULUS ROD	YIELD STRESS CYLINDER	YIELD STRESS ROD
2.10000D+06	2.10000D+06	6.00000D+03	4.00000D+03

TABLE6: INCLINATION,FRICTION COEFFICIENT,FACTOR OF SAFTEY,

CYLINDER INCLINATION 0.0

FRICTION COEFFICIENTS

CYLINDER END 0.0

ROD END 0.0

TABLE7: STATION DATA

AUTOOPTION

NUMBER OF ELEMENTS

CYLINDER 3

ROD 1

TABLE8: FIXITY CONDITIONS,ECCENTRICITY OF LOADING

NODE	FIXITY ALONG PLANE XY	FIXITY ALONG PLANE XZ	ECCENTRICITY ALONG XY	ECCENTRICITY ALONG XZ	MOMENTS ABOUT Y	MOMENTS ABOUT Z
1	PIN	PIN	0.0	0.0	0.0	0.0
5	PIN	PIN	0.0	0.0	0.0	0.0

AXIAL LOAD DISTRIBUTION IS UNIFORM

OPERATING CYLINDER PRESSURE = 2.00000D+02

ALLOWABLE CROOKEDNESS ANGLE = 7.50000D-05 AT GLAND

ALLOWABLE TOTAL LATERAL FORCE = 3.50000D+03 ON BEARINGS

```
PROGRAM SACFI  - STRESS ANALYSIS OF CYLINDERS ( REGULAR )

          N. RAVI SHANKAR          EXAMPLE PROBLEMS
             CODED ON NOVEMBER 1 1978

PROBLEM    5

    ANALYSIS FOR DETERMINATION OF STOP TUBE LENGTH METRIC UNITS

RESULTS:      ANALYSIS TO DETERMINE STOP-TUBE LENGTH

REQUIRED LENGTH OF STOP-TUBE      =  5.080D+00     CM

CORRESPONDING EXTENDED LENGTH     =  2.679D+02     CM

RESULTS WITH THIS STOP-TUBE ARE:

         CRITICAL LOAD            =  9.241D+03     KGS

         MAXIMUM FLUID PRESSURE   =  2.000D+02     KGSC

         CROOKEDNESS ANGLE        =  3.15900D-05   RAD

CYLINDER:

     MAXIMUM DEFLECTION           =  2.649D+00     CM

     MAXIMUM LONGITUDINAL STRESS= 1.248D+03     KGSC

     AT A DISTANCE FROM CYL SUP   =  1.381D+02     CM

     FACTOR OF SAFETY ON CYL      =  4.807D+00

     MAX SHEAR STRESS IN CYL      =  1.221D+03     KGSC
     AT MAX LONG STRESS POINT
     AND AT INNER SURFACE  ,

     FACTOR OF SAFETY ON CYL      =  2.457D+00

     MAXIMUM HOOP STRESS IN CYL   =  1.365D+03     KGSC

     FACTOR OF SAFETY ON CYL      =  4.396D+00

ROD      1

     MAXIMUM DEFLECTION           =  2.676D+00     CM

     MAXIMUM LONGITUDINAL STRESS= 3.638D+03     KGSC

     AT A DISTANCE FROM CYL SUP   =  1.403D+02     CM

     FACTOR OF SAFETY ON ROD      =  1.099D+00


FORCES AT SLIDING CONNECTION:

          PISTON BEARINGS (SEALS)        FORCE
                 NO

                  1                 3.140D+03  KGS

                  2                 1.294D+02  KGS


          ROD BEARINGS (SEALS)           FORCE
                 NO

                  1                 3.270D+03  KGS


F1- FORCE AT PISTON HEAD FRONT FACE  =  0.0         KGS

F2- FORCE AT STUFFING BOX FRONT FACE =  0.0         KGS

F3- FORCE AT PISTON HEAD BACK FACE   =  0.0         KGS

F4- FORCE AT STUFFING BOX INNER FACE =  0.0         KGS
    (ZERO FORCES INDICATE NO CONTACT)
```

PROGRAM SACFI - STRESS ANALYSIS OF HYDRAULIC CYLINDERS.

M. RAVI SHANKAR   EXAMPLE PROBLEMS
CODED ON NOVEMBER 1 1978

PROBLEM 6

VERTICAL LIFT CYLINDER

INPUT DATA:

TABLE 1: CONTROL DATA

PROBLEM TYPE = 1 - CRITICAL LOAD ANALYSIS & ANALYSIS FOR A FACTORED LOAD

TABLES RETAINED FROM PREVIOUS PROBLEM

2 3 4 5 6 7

NO KEEP OPTIONS EXERCISED

TABLE 2: UNITS OF MEASUREMENT

LENGTH	LOAD	PRESSURE	ANGULAR
INCH	KIPS	KSI	RAD

TABLE 3: CYLINDER DIMENSIONS

LENGTHS:

STROKE	PISTON HEAD	STUFFING BOX	END PLATE	HINGE DIST.
5.000000D+01	1.780000D+00	5.625000D-01	9.000000D-01	0.0

CYLINDER	ROD	EXTENDED	STOP TUBE
5.290600D+01	5.278300D+01	1.056890D+02	0.0

DIAMETERS:

CYL. OUTER	CYL. INNER	ROD OUTER	ROD INNER	
3.500000D+00	3.020000D+00	2.000000D+00	0.0	SOLID ROD

CYL. PIN *	ROD PIN *	PISTON HEAD @	STUF. BOX @
5.000000D-01	5.000000D-01	2.995000D+00	2.052000D+00

(* ZERO, THE END IS FIXED) (@ ZERO, OTHER OPTION IS INPUT)

CLEARANCES BETWEEN:

CYLINDER AND STUFFING BOX	CYLINDER AND PISTON HEAD @	ROD AND STUF. BOX @
0.0	0.0	0.0

(@ ZERO, OTHER OPTION IS INPUT)

TABLE 4: BEARINGS AND SEALS

PISTON BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FROM BACK FACE
5.300000D-01	3.725000D-01	1.500000D+04	0.0	1.515000D+00
1.000000D+00	3.815000D-01	4.200000D+02	0.0	7.500000D-01

ROD BEARINGS:

A WIDTH	A THICKNESS	A YOUNGS MODULUS	B STIFFNESS	DISTANCE FROM BACK FACE
1.000000D+00	1.250000D-01	1.500000D+04	0.0	1.062000D+00

(A IS USED TO CALCULATE B - HENCE, EITHER A OR B IS INPUT
ZERO'S ABOVE INDICATE THAT THEY ARE NOT INPUT)

TABLE 5: WEIGHTS AND MATERIAL PROPERTIES

WEIGHTS OF PARTS:

CYLINDER (PER UNIT LENGTH)	ROD	PISTON HEAD	STUFFING BOX
2.400000D-03	3.000000D-03	4.157000D-03	1.777000D-02

MATERIAL PROPERTIES:

YOUNGS MODULUS CYLINDER	YOUNGS MODULUS ROD	YIELD STRESS CYLINDER	YIELD STRESS ROD
2.900000D+04	2.900000D+04	7.500000D+01	4.050000D+01

TABLE 6: INCLINATION,FRICTION COEFFICIENT,FACTOR OF SAFTEY,
CYLINDER INCLINATION 1.571D+00
FRICTION COEFFICIENTS
CYLINDER END 0.0
ROD END 0.0

TABLE7: STATION DATA
AUTOOPTION

NUMBER OF ELEMENTS
CYLINDER 3
ROD 1

TABLE8: FIXITY CONDITIONS,ECCENTRICITY OF LOADING

NODE	FIXITY ALONG PLANE XY	FIXITY ALONG PLANE XZ	ECCENTRICITY ALONG XY	ECCENTRICITY ALONG XZ	MOMENTS ABOUT Y	MOMENTS ABOUT Z
1	FIX	FIX	0.0	0.0	0.0	0.0
2			2.5000+00	0.0	0.0	0.0

AXIAL LOAD MAGNIFICATION FACTORS

NODE NO	AXIAL LOAD MAGNIFICATION
1	1.000
2	2.000
3	2.000
4	2.000
5	2.000

FACTOR OF SAFETY = 1.000 ON LOAD

THE CYLINDER BUCKLED AT A LOAD OF 0.105D+02

```
00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
           N. RAVI SHANKAR          EXAMPLE PROBLEMS
              CODED ON NOVEMBER 1 1974
    1         SOLID ROD , HORIZONTAL CYLINDER, CRITICAL LOAD ANALYSIS
     1
          INCH      KIPS      KSI       RAD
 50.00    1.78      0.5625    0.9                           NO
  52.906  52.7837   105.689
 3.5      3.02      2.0       0.0       0.005     0.005     2.995     2.052

  0.530   0.3725    15000.              1.515
 1.000    0.3815    400.                 0.75               END
 1.000    0.125     15000.              1.062               END
 0.0024   0.003     0.004157  0.01777   29000.    29000.    75.       40.5
                              1.0                                      LOAD
      AUTO      3         1         CONS
          1       PIN       PIN
          5       PIN       PIN                                        END
    2       HOLLOW ROD,VERTICAL CYLINDER,ECCENTRICITY ALONG X AND Y AXES
    1    KEEP                 KEEP      KEEP                KEEP
 50.00    1.78      0.5625    0.9       0.0                 YES
 52.906   52.783    105.689
 3.5      3.02      2.00      1.5       0.5       0.5       2.995     2.052

 1.507                        1.0                                      LOAD
          1       FIX       PIN
          5       PIN       PIN  0.5       0.5                         END
    3       HOLLOW ROD ,INCLINED AT 30, ECCENTRICITY AT INTERIOR NODE
     1              KEEP      KEEP      KEEP                KEEP
          INCH      KIPS      KSI       DEG
 30.      0.001     0.001     1.0                                      STRS
          1       PIN       PIN
          3                      0.5
          5       PIN       PIN  1.0                                   END
    4         ANALYSIS FOR CRITICAL PRESSURE=2KSI, SELF OPTION
     2                        KEEP      KEEP
          INCH      KIPS      KSI       RAD
  50.00    1.78     0.5625    0.9       0.0                 NO
 52.906    52.783    105.689
 3.5      3.02      2.00                0.5       0.5       2.995     2.052

                                        2.0
      SELF      3         1         CONS
        . 1
          2 50.9
          3 52.0712
          4  53.2425
        , 5 105.689                               END
        . 1       PIN       PIN
          5       PIN       PIN                                        END
    5         ANALYSIS FOR DETERMINATION OF STOP TUBE LENGTH METRIC UNITS
     3
          CM        KGS       KGSC      RAD
 127.00   4.5       1.42375   2.286                         NO
 8.89     7.67      5.00                1.27      1.27      7.6073    5.21203

 1.3462   0.9500    1000000.            3.85
  2.5     0.95      28200.              1.90                END
  2.5     0.300     1000000.            2.70                END
 1.125    1.400     1.95      8.3       2100000.  2100000.  6000.     4000.
                                        200.      0.000075  3500.
      AUTO      3         1         CONS
          1       PIN       PIN
          5       PIN       PIN                                        END
    6         VERTICAL LIFT CYLINDER
     1
          INCH      KIPS      KSI       RAD
 50.00    1.78      0.5625    0.9                           NO
 52.906    52.783    105.689
 3.5      3.02      2.00                0.5       0.5       2.995     2.052

  0.530   0.3725    15000.              1.515
 1.000    0.3815    400.                0.75                END
 1.000    0.125     15000.              1.062               END
 0.0024   0.003     0.004157  0.01777   29000.    29000.    75.       40.5
 1.5707                       1.0                                      LOAD
      AUTO      3         1
 1.0      2.0       2.0       2.0       2.0
          1       FIX       FIX
          2                   2.5                                      END
                        THIS IS A BLANK CARD
```

Program SACFI--Guide for Data Input

PROGRAM IDENTIFICATION (Two alphanumeric cards at the beginning of run)

1	80

1	80

Format--20A4

PROBLEM IDENTIFICATION (One card at the beginning of each problem)

Prob. Name NPROB		Problem Description	
1	4	11	80

Format--20A4

Program stops if NPROB is blank

TABLE 1: CONTROL DATA (One card for each problem)

	LPRTP	2		3		4		5		6		7		8		
1	5	11	14	21	24	31	34	41	44	51	54	61	64	71	74	80

Format--LPRTP - I1; 2 to 7 - A4

LPRTP = 1--Critical load analysis and analysis for a factored load using given factor of safety

2--Analysis for a particular fluid pressure

3--Analysis to determine a stop tube length for given limiting values of crookedness angle and lateral force at the sliding connection at a given fluid pressure

If any of the following tables are same as in the previous problem and are to be retained for this problem, enter "KEEP" in the corresponding blocks 2 to 7

Enter only LPRTP for the first problem

TABLE 2: UNITS OF MEASUREMENTS (No card if TABLE 2 is retained from previous problem)

	LNTU	LODU	LPREU	LANGU	
1	11 14	21 24	31 34	41 44	80

Format--A4 for all

LNTU - Unit of lengths (ex: INCH, FEET, CM, MET, etc.)

LODU - Unit of loads (ex: LBS, KIPS, KGS, etc.)

LPREU - Unit of pressures (ex: KSI, PSI, KSCM, etc.)

LANGU - Unit of angles (enter DEG or RAD starting in column 41)

TABLE 3: CYLINDER DIMENSIONS (No cards if TABLE 3 is retained from previous problem; see Figure 34 for details)

Card No. 1--Lengths

STROK	PHL	SBL	EPTK	CHDS		LFLUID	
1	11	21	31	41	50	61 63	80

Format--LFLUID--A3; E10.3 for the rest

LFLUID - Enter "YES", for hollow rod with fluid

- Enter "NO" or blank, for hollow rod without fluid or solid rod

Card No. 2--Lengths (card No. 2 is not input for LPRTP = 3)

CL	RL	EXL	STPTB		
1	11	21	31	40	80

Format--E10.3 for all

Card No. 3--Diameters

COD	CID	ROD	RID	CPD*	RPD†	PHD**	SBD††	
1	11	21	31	41	51	61	71	80

Format--E10.3 for all

* CPD - Leave blank if cylinder support is fixed

† RPD - Leave blank if rod support is fixed

** and †† - See next card

Card No. 4--Clearances

CSBC	** PCL	†† RCL		
1	11	21	30	80

Format--E10.3 for all

**Input either PHD or PCL; if both are input, PCL will be used and PHD will be ignored

††Input either SBD or RCL; if both are input, RCL will be used and SBD will be ignored

<u>TABLE 4: BEARINGS AND SEALS</u> (No cards if TABLE 4 is retained from previous problem; see Figure 35 for details)

Piston Head Bearing Cards: (one card for each bearing)

PRW	PRT	PRE	* PRK	PRDST		NEND		
1	11	21	31	41	50	61	63	80

Format--NEND--A3; E10.3 for the rest

NEND - Enter "END" on the last piston head bearing card

* Input either (PRW, PRT and PRE) or (PRK); if PRK and some or all of PRW, PRT, and PRE are input, PRK will be used and the rest ignored

Rod Bearing Cards: (one card for each bearing)

RBW	RBT	RBE	* RBK	RBDST		NEND		
1	11	21	31	41	50	61	63	80

Format--NEND--A3; E10.3 for the rest

NEND - Enter "END" on the last rod bearing card

* Input either (RBW, RBT, and RBE) or (RBK); if RBK and some or all of RBW, RBT and RBE are input, RBK will be used and the rest ignored

PRE and RBE - Young's modulus of piston head bearings and rod bearings

PRK and RBK - Stiffnesses of piston head bearings and rod bearings per unit length (force required to compress a unit length of bearing by one unit)

TABLE 5: WEIGHTS AND MATERIAL PROPERTIES (No card, if TABLE 5 is retained from previous problem)

WC	WR	WPH	WSB	ECYL	EROD	FYCYL	FYROD
1	11	21	31	41	51	61	71 80

Format--E10.3 for all

WC and WR - Weight of cylinder and rod per unit length

WPH - Weight of piston head

WSB - Weight of stuffing box

ECYL and EROD - Modulus of elasticity of cylinder and rod, respectively

FYCYL and FYROD - Yield stresses of cylinder and rod, respectively

TABLE 6: INCLINATION, FRICTION COEFFICIENTS, FACTOR OF SAFETY, OPERATING PRESSURE, ALLOWABLE LATERAL FACE, AND CROOKEDNESS ANGLE LIMITS (No card if TABLE 6 is retained from previous problem)

CINCL	FCC *	FCR *	FS	OPPRE	ALTM	ALF	LFSTP
1	11	21	31	41	51	61	71 80

LFSTP--A4, E10.3 for the rest.

CINCL - Inclination of the cylinder with horizontal

FCC - Friction coefficient at cylinder pin. Leave blank if the particular node is fixed.

FCR - Friction coefficient at rod pin. Leave blank if the particular node is fixed.

FS - Factor of safety.

LFSTP - Factor of safety type (enter LOAD if FS is to be applied to the critical load obtained; enter STRS if FS is to be applied for the limiting stresses).

If only critical load analysis is required and no factored load analysis is required, enter FS $\leq$ 1.0 and LFSTP--LOAD or STRS blank.

OPPRE - Particular operating pressure for which analysis is required.

ALTM - Allowable crookedness angle at the sliding connection.

ALF - Allowable total lateral force on bearings.

*Refer to Figure 36 for sign convention.

TABLE 7: STATION DATA (No card if TABLE 7 is retained from previous problem)

	NCOND	NCYL	NROD		NAXCON
1	6	10	20	30	37 40

NCOND--A4, NAXCON--A4, I10 for the rest.

NCOND - Enter "AUTO" for auto option and "SELF" for self option.

NCYL - Number of elements inthe cylinder portion. The elements in the gland region are also included in NCYL. Minimum value is 3.

NROD - Number of elements in the rod region.

NAXCON - Enter "CONS" if the axial load is uniform throughout the cylinder. Leave blank if the intensity of the axial load is not uniform.

Card No. 2--Mesh data for "self option" (card No. 2 is not input if NCOND = AUTO)

NODE	COORD.	NODE	COORD.		IEND
1	10	20	30	40	48 50

Format-Node--I10, Coordinate--E10.3, NEND--A3

IEND - Enter "END" on the last mesh data card

NODE - Node number.

COORD - X coordinate of the particular node.

Card No. 3--Magnification factor for the axial load (card No. 3 is not input if NCONS is blank).

AXMULT1	AXMULT2	AXMULT3	AXMULT4	AXMULT5	AXMULT6	AXMULT7	AXMULT8	
1	11	21	31	41	51	61	71	81

Format E10.3 for all.

AXMULT1, AXMULT2--AXMULTN - Magnification factor for the axial load at the corresponding node numbers.

TABLE 8: FIXITY CONDITIONS, ECCENTRICITY OF LOADS, AND INTERIOR MOMENTS (No card if TABLE 8 is retained from previous problem)

NODCY	LCEXY	LCEXZ	ECXY*	ECXZ*	APMOY	APMOZ	NEND
1 10	18 20	28 30	40	50	60	70	78 80

Formats NODCY--I10, LCEXY, LCEXZ, NEND--A3, Rest E10.3.

NEND--Enter "END" on the last card.

NODCY - Nodal number.

LCEXY - Fixity along Y axis--enter "FIX" for fixed and "PIN" for pinned support.

LCEXZ - Fixity along Z axis--enter "FIX" for fixed and "PIN" for pinned support.

ECXY - Eccentricity along Y axis.

ECXZ - Eccentricity along Z axis.

APMOY - Applied moment about Y axis (right-hand sign convention is followed).

APMOZ - Applied moment about Z axis (right-hand sign convention is followed).

*See Figure 36 for sign convention.

Next Problem

Start from "PROBLEM IDENTIFICATION" card.

END OF RUN

At the end of last problem data set, insert a blank card (only first 4 columns need to be blank; the rest of the cards may be used for comments).

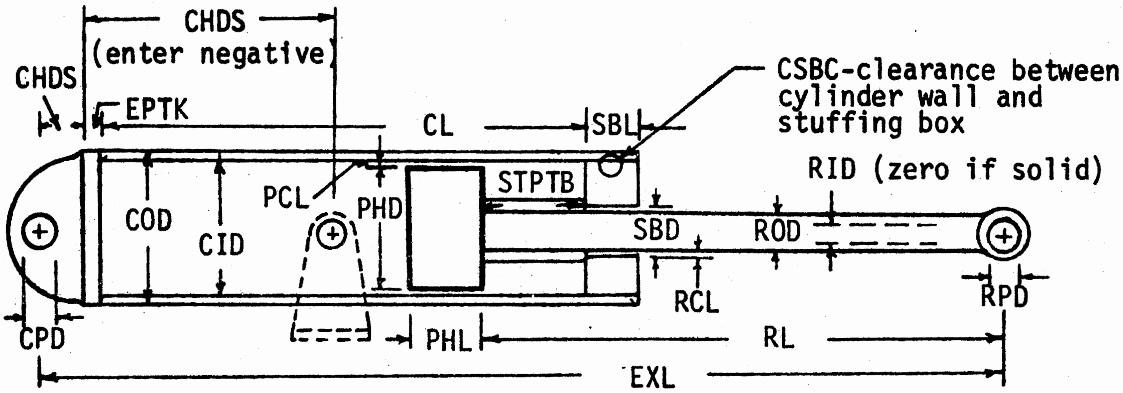

Figure 34. Cylinder Dimensions for SACFI

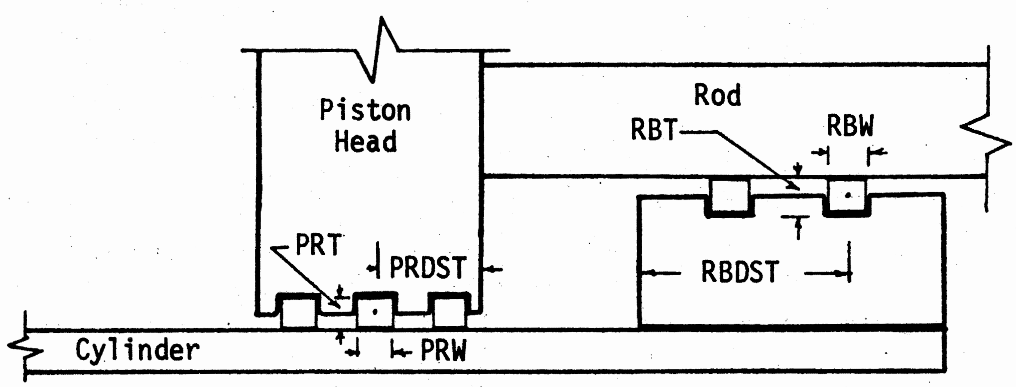

Figure 35. Dimensions of Bearings and Seals for SACFI

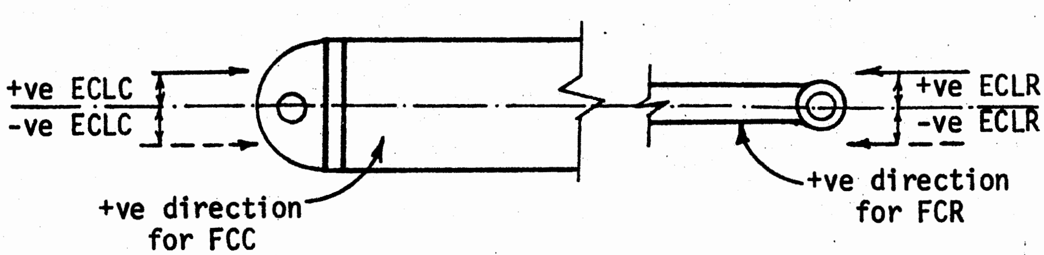

Figure 36. Sign Conventions for Eccentricities of Loading and Friction Coefficients for SACFI

VITA[2]

Narayanarao Ravishankar

Candidate for the Degree of

Doctor of Philosophy

Thesis: BIAXIAL BENDING ANALYSIS OF HYDRAULIC CYLINDERS

Major Field: Civil Engineering

Biographical:

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